Sewage Lagoons in Cold Climates

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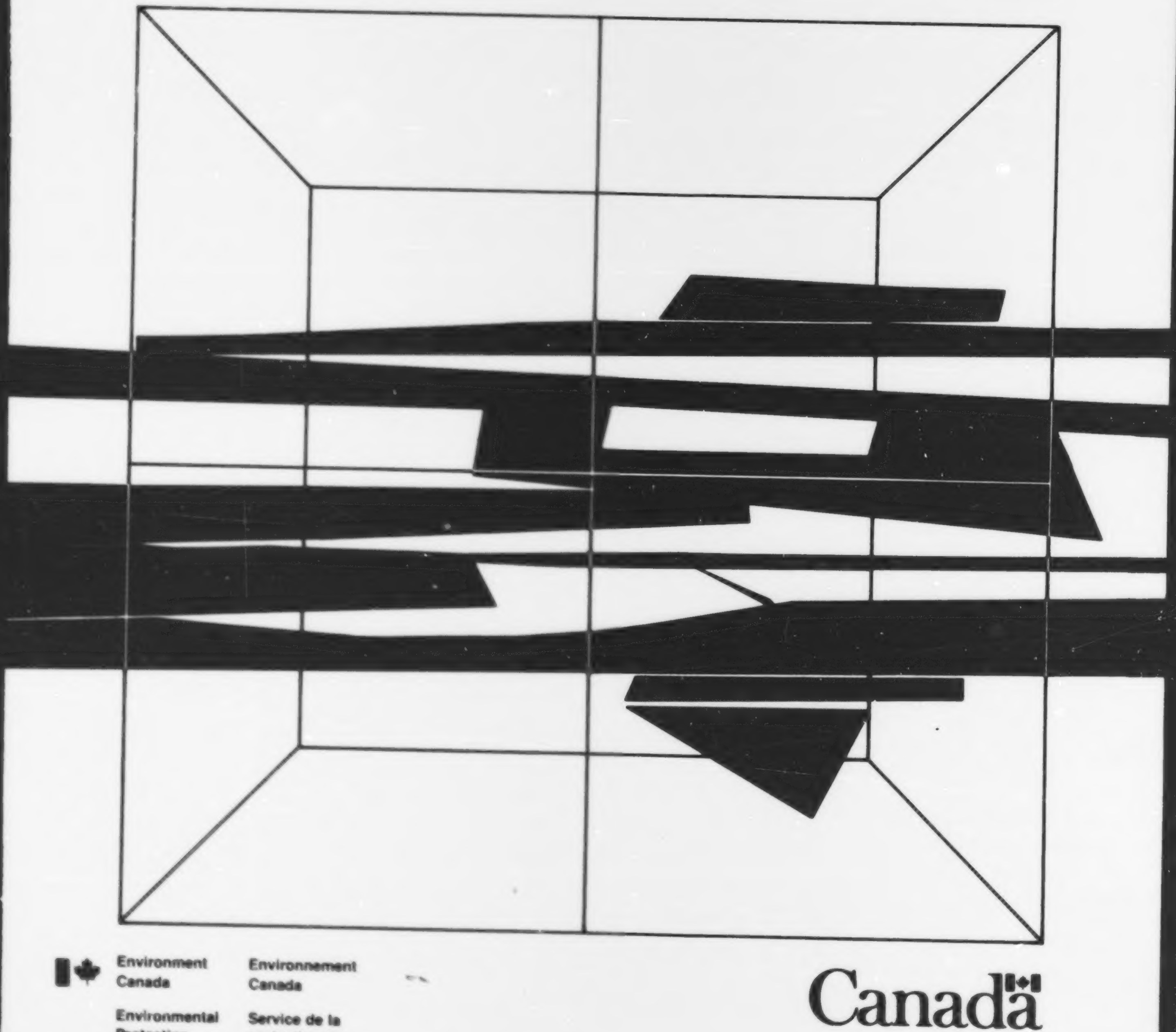
March 1985



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SEWAGE LAGOONS IN COLD CLIMATES

Technical Services Branch
Environmental Protection Service
Environment Canada

EPS 4/NR/1
March 1985

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ABSTRACT

Literature concerning sewage lagoons subject to seasonal ice cover in Canada, and the Northern USA, including Alaska was identified and compiled for this report. Information was sorted according to topic areas including: past performance, process theory, factors affecting performance, facility planning and construction, and upgrading lagoon effluents. Research and development needs in each topic area were identified.

RÉSUMÉ

On a trouvé et compilé pour ce rapport de la documentation concernant les étangs d'eaux usées touchés par une couverture de glace saisonnière au Canada et dans le nord des États-Unis, y compris l'Alaska. L'information a été triée en fonction des sujets. Mentionnons entre autres le comportement passé, la théorie relative au traitement, les facteurs touchant le comportement, la planification et la construction des installations ainsi que l'amélioration des effluents des étangs. Les besoins en matière de recherche et de développement applicables à chaque domaine ont été précisés.

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ACKNOWLEDGEMENTS

This report draws upon information found in "A Critical Evaluation of the Operation and Performance of Lagoons in Cold Climates", prepared under contract to Environment Canada by D.W. Smith and G.R. Finch, Department of Civil Engineering, University of Alberta in 1983 (University of Alberta Technical Report No. 85-2).

1 INTRODUCTION

This report reviews information on the design, operation, and performance of sewage lagoons in northern regions, where ice cover forms for a period of the year. Information from Canada, and the northern United States, including Alaska, has been studied to provide:

a) a review of literature and data on lagoons in cold regions;
b) an evaluation of present and past design and operational approaches; and
c) an identification of topics where insufficient information exists for formulation of optimal design and operation criteria and procedures.

Lagoons are often the most economical alternative for waste treatment in cold climates providing the receiving environment can cope with the effluent quality. Lagoons are biologically complex in terms of the summer symbiotic relationship between heterotrophic bacteria and photosynthetic, autotrophic algae, and the winter anaerobic conditions.

Ice cover and low water temperatures affect the capability of the natural environment to assimilate biodegradable wastes. Ice cover prevents aeration and limits the BOD (biological oxygen demand) loading that can be added to the water without adverse affects. Low water temperatures increase the life span of faecal coliforms, giving cause for health concerns.

1.1 Terminology and Development of Lagoons

In the north, two types of lagoons for the primary and secondary treatment of wastewater are of interest: facultative and anaerobic. A facultative lagoon has an aerobic layer overlying an anaerobic layer. The aerobic portion is maintained by oxygen supplied by algae and surface aeration. Anaerobic lagoons receive such a heavy organic loading that there is no aerobic zone. The principal biological reactions occurring are acid formation and methane fermentation. Anaerobic lagoons have been used effectively in the pretreatment of high-strength wastes, and are usually followed by one or more facultative ponds in series.[1]

Lagoons have been used in North America since 1901; however, they were originally used by the Chinese over 1000 years ago.[2] Many lagoons were constructed in eastern Canada during the late 1950's and early 1960's. Use of lagoons for sewage treatment in the North American Arctic evolved during the late 1950's; the first Canadian Arctic sewage lagoon was constructed in 1957, at Inuvik, NWT.

Although lagoons are not considered appropriate for disposal of human faeces alone, they may be used for all other classes of wastewater. Facultative/anaerobic lagoons as used in cold regions will seldom meet statutory effluent quality criteria during winter months without the adoption of a number of process variations which are greatly influenced by the wastewater characteristics. The policy of the NWT government has been towards using trucked/piped water systems which will produce a conventional wastewater.[3]

The characteristics of the wastes to be treated are governed by the human population size and the type of water distribution system present. In the north, waste is collected in honey bags and/or from storage tanks (using truck hauling) where water is hauled to homes, or by conventional gravity sewage systems where provided. Undiluted concentrated wastes are obtained from honey bags, and moderately diluted wastes from storage tanks. Diluted wastewaters are obtained where piped water supplies and sewer systems exist. Water flow or "bleeding" to prevent freezing in water distribution systems and sewage collection piping results in highly diluted wastewaters, a problem unique to northern communities.

Lagoons are popular across Canada because of their low capital and operating costs. During relatively warm weather and adequate sunlight, the treatment performance in terms of BOD and faecal coliform (FC) reduction is good; in cold weather and limited sunlight, the treatment performance is poor. In addition to the seasonal performance variation, cold climate lagoons have several other disadvantages including: periodic odours, short circuiting, and noxious vegetation growth. Construction of lagoons in permafrost areas also poses problems. As a result, a number of design and operational modifications have been developed to overcome climate-related treatment limitations.

The problem of cold climate biological treatment of wastewater has been studied in some detail, providing a basis for the design and operation of treatment facilities. Even though the rate of biological activity is greatly reduced during the winter months, lagoons are considered the best alternative for wastewater treatment in the north because:

a) capital and operating costs are low;
b) maintenance requirements are low;
c) energy requirements are minimal;

d) skilled operators are not required;
e) inexpensive land is available; and
f) adequate service for small populations is provided.

1.2 Inventory of Canadian Lagoons

Lagoons are common in the sparsely populated regions of Canada because they are the most cost-effective form of waste treatment. Approximately half of the wastewater treatment systems reported in Canada are sewage lagoons, with Alberta, Manitoba, Saskatchewan, Northwest Territories and Yukon Territory relying heavily (70% or more) on this form of treatment (Table 1). In 1981, there were 868 lagoon systems operating in Canada.[4,6]

"The National Inventory of Municipal Waterworks and Wastewater Systems in Canada" includes a breakdown on a community basis of: total population, population with municipal services, type of treatment facility (including lagoons), average flow rates, and other relevant information[4]. Information dealing specifically with the Yukon and Northwest Territories may be found in the 1982 report by Smith and Christensen.[5]

TABLE 1 LAGOON USE IN CANADA IN 1981 [4,6]

Location	Number of Lagoons	Number of Lagoons as a % of Treatment Facilities
Alberta	278	84
British Columbia	34	31
Manitoba	127	85
New Brunswick	58	63
Newfoundland	1	2
Northwest Territories	15	71
Nova Scotia	14	16
Ontario	128	33
Prince Edward Island	17	9
Quebec	59	21
Saskatchewan	129	92
Yukon Territory	8	70
Canada	868 (total)	48 (average)

1.3 Performance Record

Considerable performance data are documented, but a major problem with reported information is that it presents seasonal parameters as discrete data points, making it difficult to draw conclusions or establish statistically meaningful performance relationships. The best that can be obtained are ranges of variation for key performance parameters such as BOD, SS (suspended solids), nutrients, and indicator microorganisms.

A performance summary of lagoons operated in the Northwest Territories and the Yukon as of 1981 is presented in Table 2. Other relevant performance reports found in the literature are summarized in Table 3. These tables illustrate that performance reporting is inconsistent for cold climate lagoons and that summer performance is comparable to that of southern, warm weather facilities. Dawson[7] provides a good summary of lagoon performance in the Northwest Territories.

Some sources do not indicate whether the reported numbers are based on averages or individual grab samples. The organic loading is often difficult to determine since flow rates are rarely measured and lagoon geometry is not presented (Tables 2 and 3).

Another problem is the use of percent reduction for BOD, SS, and coliform organisms. The general practice is a comparison of influent and effluent concentrations, but in a multi-cell system it often is not clear if the final effluent or inter-cell values are reported. Often, no distinction is made between filtered and unfiltered BOD data, which significantly affects the interpretation. McKinney discounted the use of influent:effluent ratios in algal-based treatment systems because they are not related in this particular process.[8]

In the case of coliform reduction, the use of $\log_{10}$ reduction is preferred. It is rarely used, however, causing misleading interpretation of the data. For example: 90-percent reduction of 10^7 organisms per 100 mL may leave 10^6 organisms per 100 mL remaining. This impressive performance in reality is only one $\log_{10}$ unit reduction.[9]

Each jurisdiction has its own effluent standards. The Northwest Territories bases its quality guidelines on the dilution capacity of the receiving waters.[10] Effluent BOD requirements range from 30 mg/L for small streams to 600 mg/L for ocean outfalls. Similarly, allowable effluent suspended solids range from 35 to 725 mg/L. Permissible levels for total coliforms vary from less than 1000/100 mL to unlimited. Lagoons operated at temperatures from 15°C to 20°C are able to meet the lower value, given proper design and operation.

TABLE 2 SUMMARY OF LAGOON PERFORMANCE NORTH OF 60°

Location	Latitude (approx.)	Population Total/Served	Collection System	Lagoon Type	Number of Cells	Op. Mode	Discharge Mode	Retention Time (d)	Daily Org. Loading kg BOD	BOD$_5$ Removal %	SS Removal %	Remarks
Baker Lake, NWT	64°18'N	1062/1062	tank/bag	fac.	2	series	cont.	1891				Natural lakes
Enterprise, NWT	60°15'N	40/40	tank	anaer.	1	—	cont.					Natural pond
Eskimo Pt., NWT	61°05'N	994/994	tank/bag	anaer.	1	—	cont.					Mod. pond
Ft. Franklin, NWT	65°11'N	545/545	tank/bag	anaer.	1	—	intermit.	180				Spring & Fall discharge
Ft. McPherson, NWT	67°27'N	739/200	pipe/tank/bag	other	1	—	cont.					Natural lake
Ft. Norman, NWT	64°54'N	359/359	tank/bag	fac.	1	—	cont.					
Ft. Providence, NWT	61°21'N	554/554	tank	anaer./fac.	4	par./ser.	intermit.	365				Spring discharge
Ft. Smith, NWT	60°00'N	2297/2297	pipe	anaer./fac.	3	par./ser.	cont.	90	24/ha	50-90	80-95	
Hay River, NWT	60°51'N	3129/3129	pipe	anaer.	3	par./ser.	cont.					
Inuvik, NWT	68°21'N	2929/2929	pipe	fac.	1	—	cont.		16/ha	70-90	85	
Pine Pt., NWT	60°50'N	1647/1647	pipe	anaer.	2	series	cont.					
Rae, NWT	62°50'N	1350/1350	bag	fac.	1	—	none	long				Twin towns
Edzo, NWT	62°50'N		pipe	fac.	2	par./ser.	cont.	51				
Tuktoyaktuk, NWT	69°27'N	762/762	bag/tank	other	1	—	none	long				Natural lake
Yellowknife, NWT	62°28'N	9550/9140	pipe	fac.								
Niven Lake												Natural lake system
Faro, YT	62°11'N	1800/1800	-	anaer./fac.	-	-	-	-				
Haines Jct., YT	60°45'N	450/350	-	anaer.	-	-	-	-				
Teslin, YT	60°10'N	300/150	-	anaer./fac.	-	-	-	-				
Watson Lake, YT	60°02'N	809/600		fac.	2	series	intermit.			50		Discharge bimonthly
Whitehorse, YT	63°43'N	16 929/15 200										
Crestview		/200		anaer./fac.	—	—	—	—	—	—	—	
Porter Creek		/5000		anaer.	4	ser.	cont.	17	—	39	53	
Whitehorse		/10 000	pipe	anaer.	4	par./ser.	cont.	20	0.01/m^3	41	60	

TABLE 3 SUMMARY OF PAST PERFORMANCE OF TYPICAL LAGOONS

Location	Latitude (approx.)	Population Total Served	Lagoon Type	Number of Cells	Op. Mode	Discharge Mode	Retention Time (d)	Daily Organic Loading kg BOD	BOD_5* Removal %	SS* Removal %
Moose Jaw, Sask.	50°20'N	35 000	anaer.	2	par.	cont.	7	1212/ha	40	65
			aerobic	2	par.	intermit.	93	54/ha	85	65
Hay River, NWT	60°51'N	1700	anaer.	2	par./ser.	cont.	5	0.03/m^3	43	81
Fayette, Missouri	40°00'N	3144	fac.	6	par./ser.	cont.	88-150	20-100/ha	72-90	--
Canora, Sask.	52°00'N	--	fac.	1	--	--	--	12/ha	66-100	78-95
Wynyard, Sask.	52°00'N	--	fac.	2	series	--	--	--	85	37
Kamsack, Sask.	52°00'N	--	fac.	1	--	--	--	13/ha	50-95	21-79
Daysland, Alta.	52°00'N	350	anaer.	1	--	cont.	6.0	3000/ha	50	--
Stony Plain, Alta.	52°00'N	1040	anaer./fac.	4	ser.	cont.	200	10-5000/ha	69-98	--
Calmar, Alta.	52°00'N	600	anaer./fac.	2	ser.	cont.	65	100/ha	72	--
Holden, Alta.	52°00'N	450	fac.	1	--	cont.	275	22/ha	72-82	--
Lacombe, Alta.	52°00'N	2835	fac.	1	--	cont.	205	28/ha	38-82	--

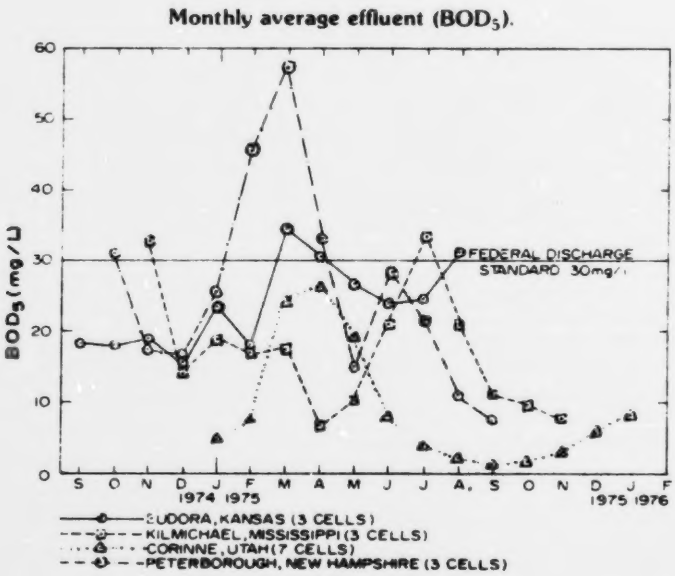
* winter to summer average removal

During winter, with the presence of ice and snow cover and near-freezing water temperatures, lagoon performance deteriorates to that of a sedimentation basin. The decline in BOD, SS, and FC removal in typical cold region facultative lagoons is illustrated in Figure 1. In recognition of these problems, most lagoons are designed for intermittent, controlled discharge with long retention times (up to 2 years).

It is evident from the literature that problems such as:

1) failure to meet effluent standards during winter,
2) odour,
3) sludge accumulation,
4) erosion,
5) safety,
6) insects, and
7) water loss,

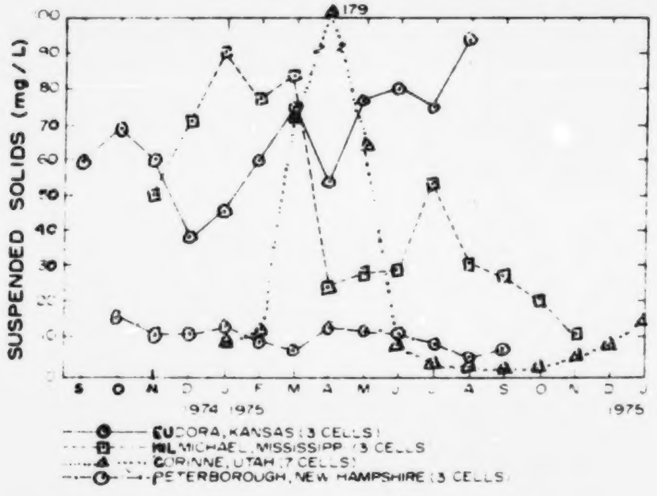
are common to many lagoon systems.


Monthly average effluent (BOD_5).

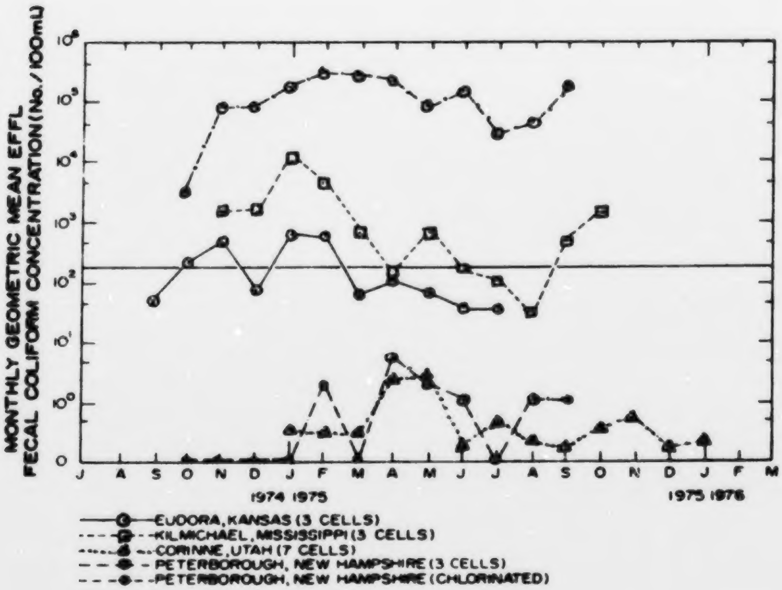
(a) BOD

FIGURE 1 SEASONAL PERFORMANCE VARIATION[11]

Monthly average effluent SS for typical facultative lagoons.



(b) Suspended Solids



(c) Faecal Coliforms

FIGURE 1 SEASONAL PERFORMANCE VARIATION (Cont'd)

2 THEORY OF LAGOON TREATMENT

Facultative lagoons, with their aerobic surface zone containing photoautotrophic algae and aerobic bacteria, are the most common type of lagoon used in Canada (Figure 2). Bacteria and algae exist in symbiosis where bacteria generate the carbon dioxide used by the algae as a carbon source. The algae then produce oxygen and new cells under adequate lighting conditions.

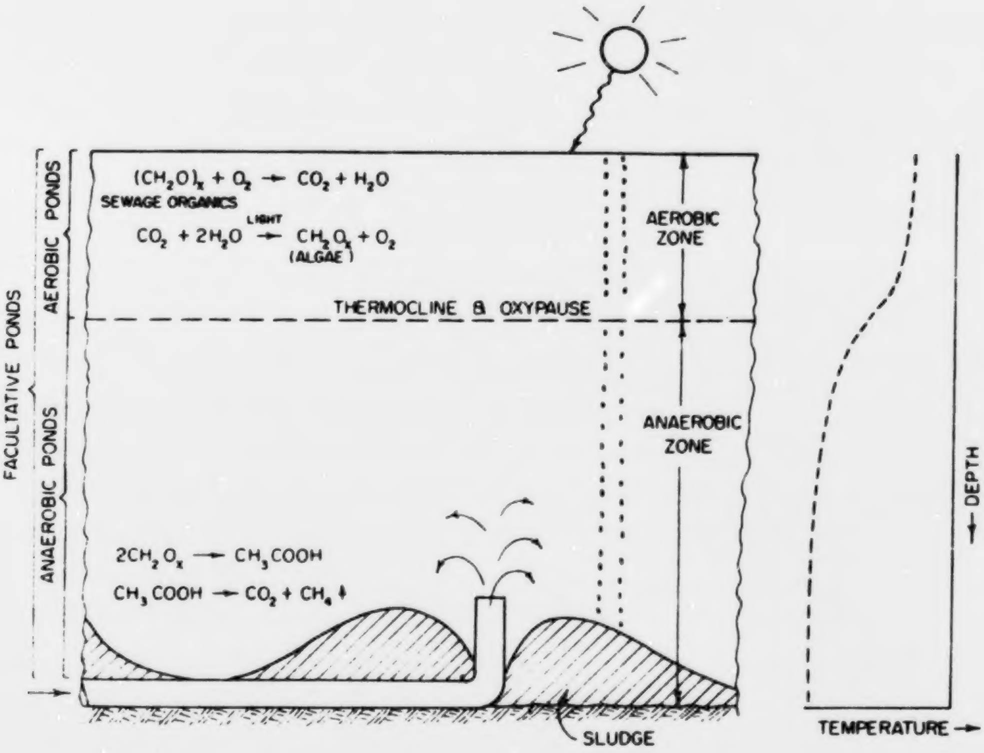

$(CH_2O)_x + O_2 \rightarrow CO_2 + H_2O$
SEWAGE ORGANICS
$CO_2 + 2H_2O \xrightarrow{LIGHT} CH_2O_x + O_2$
(ALGAE)
AEROBIC ZONE
THERMOCLINE & OXYPAUSE
ANAEROBIC ZONE
$2CH_2O_x \rightarrow CH_3COOH$
$CH_3COOH \rightarrow CO_2 + CH_4 \uparrow$
SLUDGE
AEROBIC PONDS
ANAEROBIC PONDS
FACULTATIVE PONDS
DEPTH
TEMPERATURE

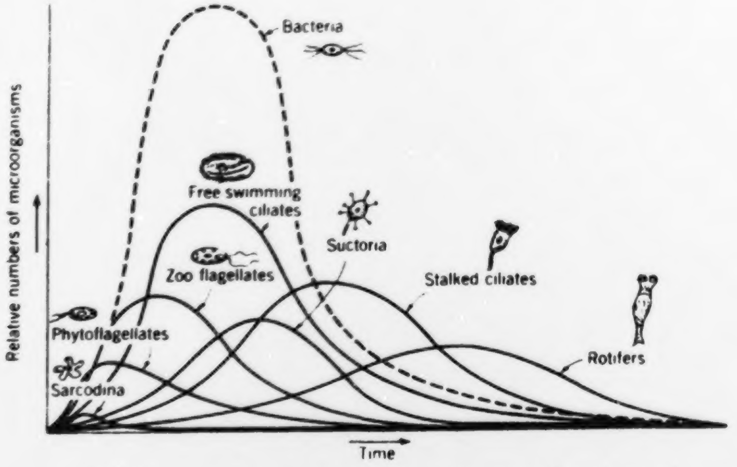
FIGURE 2 A SCHEMATIC OF A FACULTATIVE LAGOON[12]

The anaerobic benthic zone of the facultative lagoon contains obligate anaerobes which digest the deposited organic solids and cell material. A population of facultative anaerobes metabolizing suspended organic matter is found in the "transition zone". Anaerobic digestion of benthic sludge has a significant effect on sludge accumulation in cold climate lagoons, where the rate of the process is greatly reduced at temperatures lower than 19°C. The following sections describe the processes involved in both aerobic and anaerobic zones.

2.1 Microbiology

Two main types of microbial cells stabilize wastes in a lagoon system: eucaryotic cells (those cells having a true nucleus) and procaryotic cells (those not having a true nucleus). Bacteria and cyanotrophs (blue-green algae) are procaryotes and algae, fungi and protozoa are eucaryotes.

Maximum efficiency occurs when a proper mix of microorganisms is present. A typical mix for an activated sludge is shown in Figure 3. This population mix is similar to the aerobic region of a facultative lagoon except for the algae.



Relative growth of microorganisms in stabilization of liquid organic wastes. (*Note.* Numbers of microorganisms are not to same scale, but are expanded for clarity.)

FIGURE 3 TYPICAL POPULATION MIX OF ACTIVATED SLUDGE[13]

2.1.1 Bacteria.

Metcalf and Eddy noted that the aerobic bacteria found in a facultative lagoon were similar to those of activated sludge and the anaerobic bacteria were the same as those found in anaerobic digesters.[2] The bacteria found in activated sludge are mainly gram-negative heterotrophs with fewer numbers of autotrophs. These bacteria include species of the genera: Pseudomonas, Zooglea, Achromobacter, Flavobacterium, Nocardia, Bdellovibrio, and Mycobacterium. The autotrophic group includes members of the genera Nitrosomonas and Nitrobacter.[2, 14] The most common facultative aerobes found are: Pseudomonas spp., Vibrio, Aeromonas, and Chromobacterium.

Cyanotrophs (commonly known as blue-green algae) are aerobes found in lagoons but not in activated sludge. Like algae, cyanotrophs are able to assimilate simple organic compounds while utilizing carbon dioxide as the major carbon source, or grow in a completely organic medium. Cyanotrophs produce oxygen as a by-product of photosynthesis, providing an oxygen source for the other organisms. The genera Oscillatoria and Anabaena, which are nonmotile photoautotrophs unable to grow in the dark and on organic substrates, are typical of the cyanotrophs which may be found in large numbers in lagoons.[15, 16]

Conversion of odorous sulphide compounds to elemental sulphur or sulphate by the sulphur bacteria is a significant factor for odour control in facultative and anaerobic ponds. Aerobes which oxidize sulphide include Thiopedia, Thiocapsa and Chromatium (the purple and green sulphur bacteria).[8] Other groups of organisms are involved in the reduction of sulphur. These anaerobes include Desulfovibrio, which is the most common sulphate reducer.

The anaerobic zone contains two main groups of obligate organisms: the so-called acid formers, and the methane generators. The "acid formers" which convert complex organic material into simple alcohols and acids, include members of the genera Clostridium, Peptococcus, Actinomycetes, Bifidobacterium and Corynebacterium. The activity of these bacteria is important since they provide one of the substrates for the final reduction of the organic material into methane gas by the methanogenic bacteria. Methanogenic organisms include Methanobacterium, Methanococcus, Methanospirillum, and Methanosarcina.[2, 17]

Acid-forming bacteria do not limit the rate of anaerobic decomposition and do not require thermophilic temperatures for optimum growth as do the methanogenic bacteria. The acid-forming bacteria also maintain a near-optimum pH range for their existence through their own acid production. Schneiter et al. speculated that facultative, psychrophilic bacteria were involved in reducing sludge volumes in Alaskan aerated lagoons.[18]

The microbial populations of lagoons respond more to natural environmental change than those in activated sludge plants. Seasonal variations in temperature and competition for food largely determine the dominant group of organisms. Pseudomonas, for example, dominate because of their ability to utilize a wide range of organic substrates.[15]

2.1.2 Algae. Algae constitute a group of organisms that are autotrophic, utilize inorganic nutrients such as phosphate, carbon dioxide, and nitrogen and usually have photosynthetic pigments.

Three major groups of algae are found in lagoons: Chlorophyta (green algae), Euglenophyta (euglenoid algae) and Chrysophyta (yellow-green and golden-brown algae).

The genera of algae found in lagoons have been well documented.[19-23] Gloyna found Chlorella, Scenedesmus, and Chlamydomonas to be the most common green algae, Euglena to be the most common euglenoid algae, and Nitzschia to be the most common green-brown algae.[24] Euglena and Chlamydomonas are the hardiest algae. Given sufficient light, aerobic conditions can be maintained during the winter, as confirmed by the presence of viable psychrotrophic algae under ice cover.

Algae and bacteria together comprise the essential elements of a successful stabilization pond operation. Bacteria break down the complex organic waste components aerobically and anaerobically into simple products which are then available for use by the algae. Algae in turn, produce the oxygen necessary for maintaining the aerobic environment for the bacteria to perform oxidative functions.

Uhlmann studied phytoplankton production in hypereutrophic waters similar to sewage lagoons.[25] Under conditions of optimum nutrients, temperature, detention time, and light, the algal mass never achieved predicted concentrations. This was attributed to predacious zooplankton (crustaceans, rotifers).

Algal concentration was a function of algal species, pH and concentration of dissolved oxygen.

2.1.3 Protozoa and Higher Animals. Protozoa, crustaceans and rotifers such as Paramecuim, Glaucoma, Euplotes, Colpidium and the stalked ciliate Vorticella are found in lagoons. The ciliated protozoa (Ciliata) are highly mobile and adapted to the efficient capture of bacteria.

Crustaceans filter large quantities of water to feed on bacteria and algae. The most important crustacean is Daphnia, but Cyclops, Diatomus and Moina genera may be found as well.

Rotifers are the scavengers of the lagoons, cleaning up large organic particles, algae, bacteria and cellular debris.

2.2 Biochemical Conversions

Microbial cells composed of nucleic acids, carbohydrates, proteins and lipids contain about 50% carbon, 20% oxygen, 10 to 15% nitrogen, 8 to 10% hydrogen, 1 to 3% phosphorus, 0.5 to 1.5% sulphur and many trace metals on a dry weight basis.[26] Commonly used chemical expressions for cell material are $C_5H_7O_2N$ and $C_5H_9O_{2.5}N$.[8, 17]

Aerobic stabilization of organics in a lagoon system may be described by two simplified equations:

$$5CO_2 + 3H_2O + NH_3 \rightarrow C_5H_9O_{2.5}N + 5.25\,O_2 \qquad (1)$$

$$6(CH_2O)_x + 5O_2 \rightarrow (CH_2O)_x + 5CO_2 + 5H_2O \qquad (2)$$

Equation 1 describes algal activity. Equation 2 represents the aerobic, metabolism of heterotrophic bacteria.

An obligate aerobe, Thiobacillus, is capable of oxidizing sulphides. Its presence relies on adequate oxygen and sulphide concentrations, but since molecular oxygen quickly oxidizes sulphide, conditions are rarely present to encourage its growth in a lagoon.

Anaerobic biochemical conversions involve the reduction of organic compounds to organic acids (Equation 3) and subsequent methane production (Equation 4).

$$5\,(CH_2O)_x \rightarrow (CH_2O)_x + 2CH_3COOH \qquad (3)$$

$$2.5\,CH_3COOH \rightarrow (CH_2O)_x + 2CH_4 + 2CO_2 \qquad (4)$$

The reduction of sulphates (Equation 5) and the oxidation of sulphides (Equation 6) cause objectionable odours.

$$1.5\,CH_3COOH + SO_4 \rightarrow (CH_2O)_x + H_2S + 2CO_2 + 2OH^- \qquad (5)$$

$$2(CH_2O)_x + 2CO_2 + 2H_2S \rightarrow 4(CH_2O)_x + 2H_2O + 2S \qquad (6)$$

Stumm and Morgan discussed the effects of aerobic respiration and photosynthesis on the alkalinity of an aqueous system.[27] Qualitative effects of the various biochemical processes on alkalinity are summarized in Table 4.

The evolution or consumption of carbon dioxide in an aqueous system does not change the alkalinity, since protons are not evolved. Aerobic decomposition by heterotrophs, therefore, will produce carbon dioxide, decreasing the pH without altering the alkalinity. Similarly, algal growth consumes carbon dioxide, causing the pH to rise. Again the alkalinity of the system will remain unchanged unless the pH is elevated to the

TABLE 4 PROCESSES AFFECTING ALKALINITY[27]

Process	Alkalinity Change
Aerobic Respiration (no nitrite/nitrate decomposition)	None
Photosynthesis (no assimilation of ammonia)	None
Nitrification	Decrease
Denitrification	Increase
Sulphide Oxidation	Decrease
Sulphate Reduction	Increase

point where calcium carbonate precipitates and causes a reduction in the alkalinity. At pH values greater than 10, biological activity is inhibited. Algae autorespire at night, producing carbon dioxide, causing the pH to drop. It is essential for efficient biological performance, therefore, to have sufficient alkalinity to buffer the diurnal variations in pH.

Biological processes usually remove the colloidal material effectively, except during periods of low temperature. Biological flocculation is an important mechanism, promoting adsorption and sedimentation. Al-Layla and Middlebrooks reported autoflocculation of algae at temperatures greater than 10°C in the presence of 100 mg/L of alum.[28] This has not been studied in depth for lagoon applications.

Nitrification-denitrification occurs in lagoons and is defined by the biochemical reactions shown in equations 7, 8 and 9.[29] Equations 7 and 8 require aerobic conditions, whereas 9 is carried out by facultative bacteria.

$$2NH_3 + 3O_2 \rightarrow 2NO_2^- + 2H + 2H_2O \qquad (7)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \qquad (8)$$

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2 \qquad (9)$$

The bacteria responsible for nitrification are Nitrosomonas and Nitrobacter. A number of facultative organisms such as Pseudomonas, Achromobacter, Flavobacterium and Bacillus perform denitrification.

A mathematical model developed by Reed described nitrogen removal at various levels of temperature and pH.[30] Separate rate constants were evaluated for 4°C, 8°C and 24°C. Testing the model with data from Alberta produced reasonably good results. Reed indicated the removal equation was applicable to typical pond systems located in arctic, subarctic or temperate climates.

2.3 Sedimentation

Sedimentation is the most important physical process that occurs within a lagoon. The terms coagulation and flocculation respectively describe the destabilization and transport processes involved in solids removal. Four types of sedimentation have been classified:

> Type I - Discrete Particle Settling:
>
> Occurs when grit is deposited in the vicinity of the lagoon inlet where the flow velocity decreases to essentially zero;[11] this is described by Stokes's Law.
>
> Type II - Flocculent Settling of Dilute Suspensions:
>
> Is important for the removal of suspended solids. It is greatly dependent upon depth and residence time for maximum clarification efficiency.[31] The dispersed solids of various physical and chemical characteristics gradually flocculate as agglomeration occurs and faster particles overtake slower ones.[16]
>
> Type III - Hindered Settling:
>
> Occurs at the bottom of the water column where the suspended solids concentrations are highest. It describes the transition between flocculent settling and sludge compression. Oxygen uptake increases leading to the anaerobic conditions found in the underlying sludge.
>
> Type IV - Sludge Compression:
>
> Occurs slowly as a result of consolidation within the settled sludge itself. Because sludge deposits are anaerobic and gelatinous in nature, they are difficult to dewater.

Reports indicate that Type II clarification consistently provides removal of 40 to 70 percent of the suspended solids in facultative lagoons.[32-35] This is equivalent to primary treatment. Type II clarification does not remove the very slow settling and colloidal particles which remain in suspension due to their small size and high electrostatic charges. These particles will not settle until converted to a settlable form. Sludge accumulation reduces lagoon volume, potentially leading to reduced detention times and a shorter operational life.

3 PERMAFROST AND SOIL TYPES

The term permafrost was defined by Johnston as "the thermal condition in soil or rock of having temperatures below 0°C persist over at least two consecutive winters and the intervening summer".[36] Permafrost occurs as three different types: continuous, discontinuous, and sporadic, which are described in terms of increasing mean annual ground temperature. Continuous permafrost ranges from -5°C to -15°C and discontinuous from a fraction below 0°C to -5°C. Permafrost has also been called "cold" (<-4°C) and "warm" (-4° to near 0°C).[37] Sporadic permafrost occurs where climate and terrain allow. The distribution of permafrost in Canada is shown in Figure 4.

The typical "trumpet" curve of the ground temperature regime in a permafrost region is illustrated in Figure 5. Only the monthly mean minimums and maximums are shown by the curve. A shallow depth of frozen ground thaws each summer to form an active layer whose thickness varies with climatic conditions. Brown discussed the factors influencing the active layer depth in detail.[38]

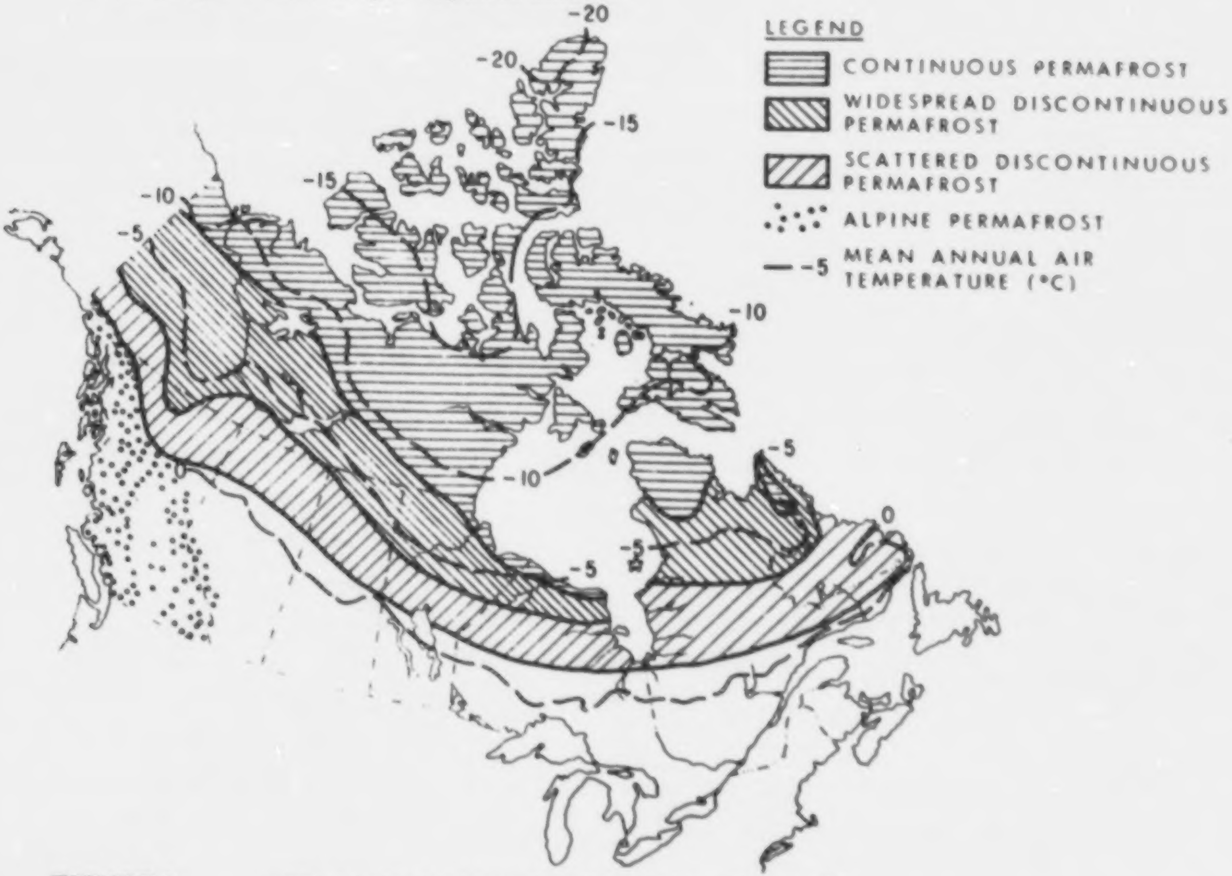

LEGEND
CONTINUOUS PERMAFROST
WIDESPREAD DISCONTINUOUS PERMAFROST
SCATTERED DISCONTINUOUS PERMAFROST
ALPINE PERMAFROST
-5 MEAN ANNUAL AIR TEMPERATURE (°C)
-20
-20
-15
-15
-10
-5
-10
-10
-5
-5
-5
-5
0
0
0

FIGURE 4 PERMAFROST DISTRIBUTION IN CANADA[39]

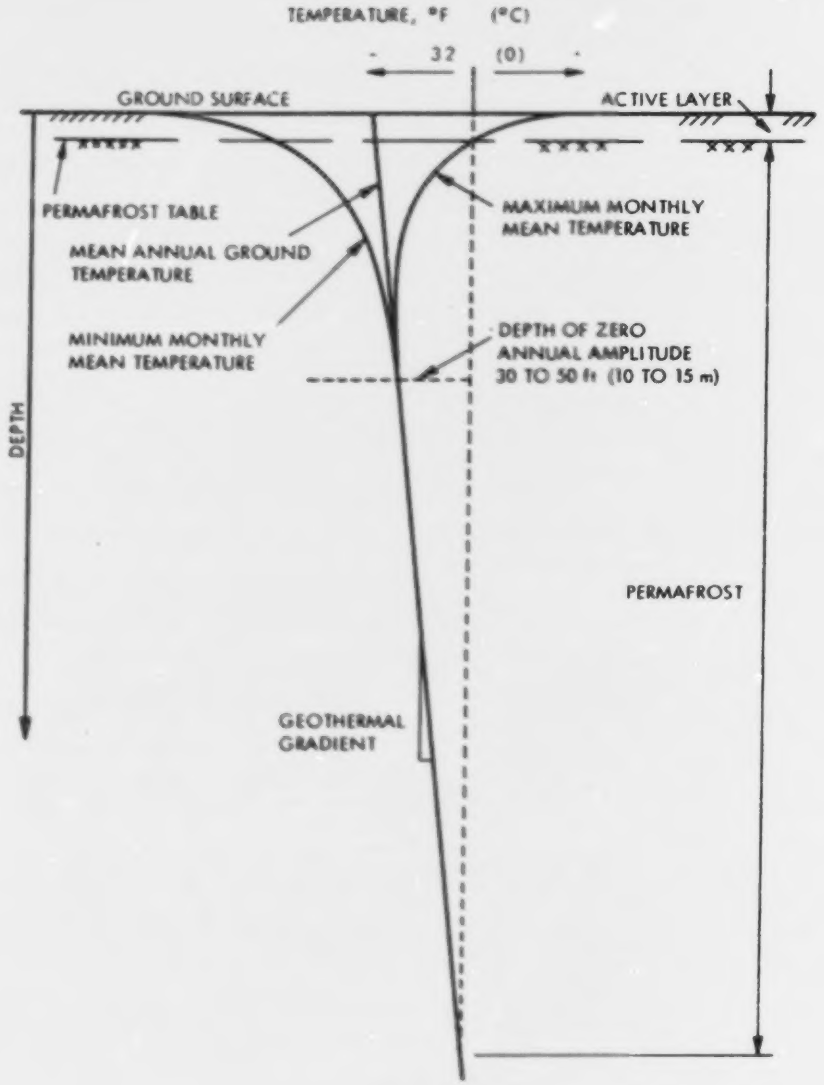

TEMPERATURE, °F (°C)
- 32 (0) +
GROUND SURFACE
ACTIVE LAYER
PERMAFROST TABLE
MEAN ANNUAL GROUND TEMPERATURE
MINIMUM MONTHLY MEAN TEMPERATURE
MAXIMUM MONTHLY MEAN TEMPERATURE
DEPTH OF ZERO ANNUAL AMPLITUDE 30 TO 50 ft (10 TO 15 m)
DEPTH
PERMAFROST
GEOTHERMAL GRADIENT

FIGURE 5 TYPICAL GROUND TEMPERATURE REGIME IN PERMAFROST[37]

Frozen soil has substantially different properties of strength, deformation, and permeability than unfrozen soil. The soil grain size distribution influences the consequences of changes in the ground thermal regime caused by lagoons. Many frozen sands and gravels have a limited amount of ice contained within their pore space which results in no adverse behaviour if subjected to thawing. On the other hand, ice-rich silts and clays are undesirable in the thawed state because the excess water may create high pore water pressures, producing unstable soil conditions. Fine-grained soils are acceptable if permafrost is absent, such as in areas adjacent to large rivers, lakes, or the ocean where the heat transfer has caused soils to thaw. These soils are also acceptable if upon thawing, the finer grained soils do not generate excess pore water pressures.

Soil samples should be described using the classification system for frozen soil suggested by Linell and Kaplar,[40] which consists of three steps:

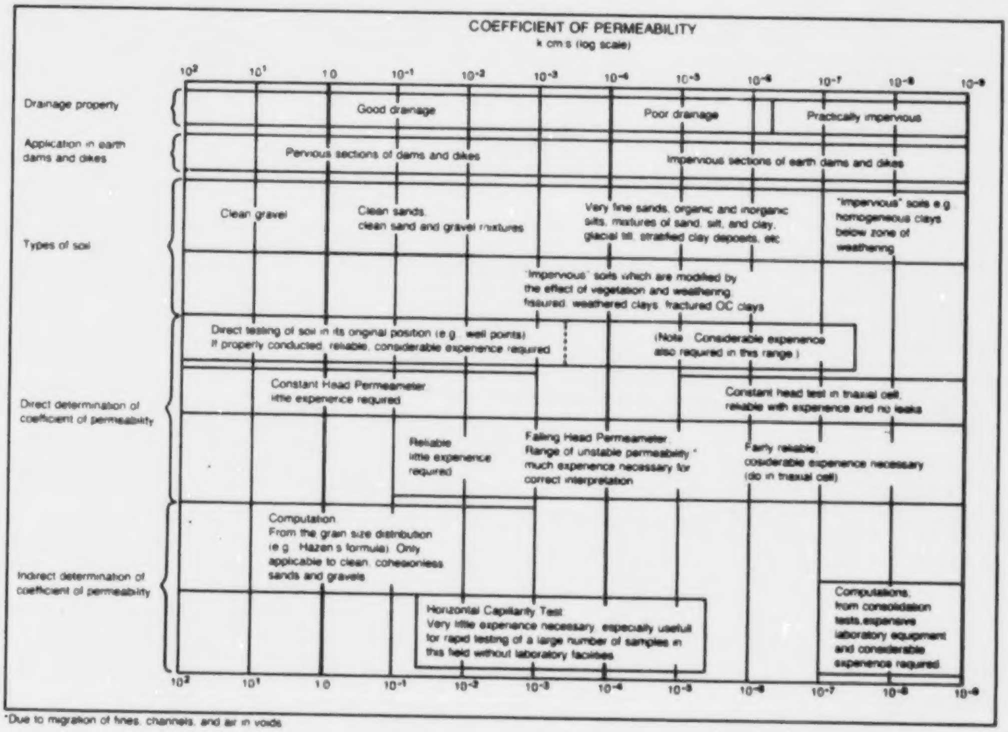
a) Use of the Unified Soil Classification System, outlined by the U.S. Army Corps of Engineers, to describe the soil phase without reference to its frozen state.
b) A description of the characteristics of the soil when frozen. This includes a description of the ice, whether or not visible, and its effect on the soil matrix.
c) A description of the ice when it occurs in layers greater that 25 mm. This includes the presence of soil inclusions and soil types.

Surface soil in the north commonly consists of decomposed and disintegrated organic material. High compressibility and moisture content restrict its use for berm foundations unless special precautions are taken. Peat has been used as a construction material for impoundment structures but excessive deformation must be prevented.

Compressibility and permeability were found to be important when evaluating the possibility of constructing berms on peat deposits. When the peat subgrade is thick and the amount of construction material limited, this may be an attractive method of construction.

Silt and clay comprise fine-grained soils which feature reduced permeabilities and higher frost susceptibility than coarse-grained soils. Liquid impoundments founded on fine-grained materials have reduced liquid losses but may suffer from thaw settlement as the material warms beneath the lagoon bottom. Where permafrost is absent, such as in thaw windows, saturated fine-grained soils may experience considerable consolidation settlement.

Coarse-grained soils include sand and gravel which characteristically have a high permeability. Well graded, coarse-grained soils are readily compacted and form stable structures. Settlement and frost-heave problems are not usually associated with foundations on these materials. Lagoons founded on, or constructed of, coarse-grained soil must be sealed to prevent seepage and embankment failures at inlet and outlet structures. Permeability ranges of some typical soils are summarized in Figure 6.



*Due to migration of fines, channels, and air in voids

Permeability, drainage, soil type, and methods to determine the coefficient of permeability

FIGURE 6 SOIL PERMEABILITY RANGES[41]

In the frozen state coarse-grained soils generally have increased strength and reduced permeability. High ice content in the soil may produce large amounts of deformation under load. These materials are normally not used in the frozen state since it is virtually impossible to prevent them from thawing. When thawed, the frozen properties disappear creating potentially unstable conditions.

4 FACTORS AFFECTING LAGOON PERFORMANCE

4.1 Climatic Influences

Lagoons have been used for wastewater treatment from the tropics to the arctic, but each climate exerts its own special effects which must be accounted for in design and operation. Climatic conditions, therefore, greatly affect the performance of lagoons.

4.1.1 **Temperature.** The single most important factor affecting lagoon performance is temperature. It not only affects the biological and physical-chemical processes, but influences ice cover, water density, mixing, and biological population distribution. Biological activity is reduced in cold environments; however, there is evidence that it does not stop completely under aerobic conditions.[42, 43]

Photosynthetic oxygen production and biological degradation rates are greatly influenced by temperature variations. Microorganism die-off and biological kinetic rates decrease with temperature, but the processes are not well understood. McKinney[8] stated that sudden changes in temperature kill the algae population, whereas gradual changes may allow acclimatization. Consequently, it is desirable to determine a method which will promote a gradual change in temperature allowing different populations to become established.

The physical properties of water such as viscosity and density are changed by temperature. Maximum density of water occurs at 4°C which is an important factor in thermal stratification. Viscosity increases as temperature decreases, adversely affecting sedimentation and flocculation. It has been speculated that supercooling and freezing of algal protoplasm have resulted in algae die-off during rapidly decreasing temperature changes in the autumn.[8]

Girling et al.[44] observed nitrification at temperatures below 10°C which contradicted findings by Grube and Murphy.[45] Sutton et al. reported the results of a pilot study which indicated the feasibility of biological denitrification at temperatures as low as 5°C.[46]

Sludge build-up in cold climates has been well documented, yet only recently has thorough research been carried out.[18, 47] Oswald found that sludge accumulated when temperatures dropped below 19°C in the sludge zone, accompanied by a marked drop in methane production.[12] Grady and Lim found that small changes in temperature could quickly upset the biological balance in anaerobic digestion.[26] They speculated that nonmethanogenic bacteria were sensitive to low temperatures (<15°C) and stopped metabolising organic matter.

Schneiter found from a survey of 31 cold-climate municipal lagoons that 15 had total sludge accumulations ranging from less than 100 mm to greater than 600 mm.[18, 47] Middlebrooks et al. reported sludge accumulation rates in Canadian and Alaskan lagoons ranged from 0.25 to 0.40 m^3/day/1000 people, the higher rate for sites at the highest latitude.[11] Clark et al. reported that anaerobic lagoons operated in the Prairie provinces accumulated sludge over the same range as the facultative lagoons in the north.[48]

4.1.2 Thermal Stratification. The effects of thermal stratification, a temperature-related phenomenon, on cold climate lagoons have been studied in some detail.[49-51] Thermocline position is a function of seasonal air temperature and light penetration which in turn is a function of turbidity and algal concentration. Stahl and May suggested that the depth and area of a water body are related to the formation of thermoclines.[49] The water body has a tendency to form a thermocline when the depth is great. Formation of thermoclines is inversely proportional to the area of the water body. Thermocline formation is beneficial in that it promotes more even distribution of organic loading from the inlet of the lagoon. When the raw sewage is warmer than the lagoon contents it is halted by the colder denser water below leading to short circuiting of flow at shallow depths.[11, 12, 51]

Major turnovers occur in the spring or early summer when the water above the epilimnion is warmer (>4°C) than the denser, colder water below and in the late summer/autumn when the upper water cools below 4°C.[52] The turnover eliminates thermal stratification and brings some of the previously deposited solids into the water column, increasing BOD and releasing any odiferous gases previously trapped in the hypolimnion.

4.1.3 Wind. Wind promotes aeration and mixing but may also contribute to short circuiting. Some authors have emphasized the importance of wind in maintaining well-mixed conditions in a lagoon and have generally agreed that pond design should promote wind access.[53] Middlebrooks et al. agreed with the principle of wind mixing to enhance lagoon performance and stressed that alignment of the lagoon inlet-outlet axis perpendicular to the prevailing wind direction was essential in reducing the effect of wind-induced short circuiting.[11]

4.1.4 Sunlight.

Since photosynthetic oxygen production is of primary concern in a sewage lagoon, sunlight and light penetration are important. High latitudes, combined with heavy ice and snow cover, essentially eliminate the possibility of photosynthesis during the winter whereas long hours of sunlight during the summer promote oxygen production.

During summer operation, light penetration is a function of algal concentration and can be estimated by the Beers-Lambert Law:[54]

$$I = I_0 e^{-kxd}$$

where:
I = light intensity at depth, d (erg/cm^2·s)
I_0 = incident light intensity (erg/m^2·s)
k = absorption coefficient (cm^2/mg)
x = concentration of algal cells (mg/cm^3)
d = depth (cm)

Algal species have a variety of preferred light intensities and wavelengths. The presence of strong ultraviolet (UV) radiation contributes to lower microorganism numbers.[51, 55]

4.1.5 Ice and Snow Cover.

Extended periods of cold air temperatures lower the water temperature (<4°C), resulting in reduced water density and subsequent ice formation. Once complete ice cover is established, surface aeration is eliminated and light penetration is reduced.

Sparling referred to Croxton et al. of the Minnesota Academy of Science, who found that 33 percent of the incident light penetrated through 350 mm of ice.[56] The same investigators reported 0.27 percent of the incident light passed through 100 mm of snow.

Normally, ponds in the far north accumulate one to two metres of ice cover during winter with varying amount of snow cover (Figure 7). Rapid algae-killing temperature changes in the autumn and heavy ice cover in winter contribute significantly to the anaerobic conditions found in northern lagoons. Even with thin ice, any accumulation of snow reduces the light to near zero. This reduction has an adverse effect on photosynthetic reoxygenation. Snow cover, however, insulates the surface, reducing heat loss and subsequent ice thickness.

4.2 Biological and Chemical Influences

4.2.1 Biological Influences.

Halvorson et al. found stabilization activity to be a function of the number of bacteria, the temperature of the wastewater, and the nature of

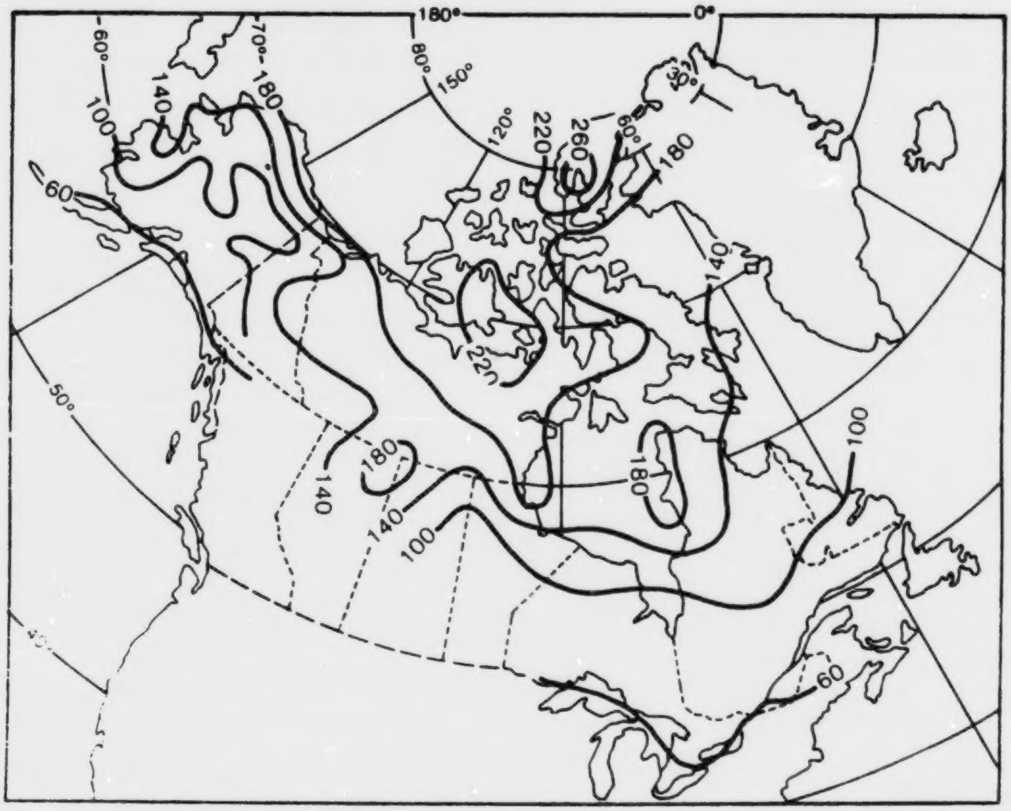


FIGURE 7 MAXIMUM ICE THICKNESS OBSERVATIONS (cm)[39]

the substrate.[57] Seasonal variation in temperature and competition for food largely determine the dominant group. Eckenfelder and Englande believed the food: microorganism (F:M) ratio was the most influential parameter in determining process temperature sensitivity.[58] A relatively high F:M ratio in lagoons, due to low microbial populations, was purported to be responsible for reduced efficiencies.

Thirumurthi presented a table outlining the concentrations of toxic organics that cause a 50 percent chlorophyll reduction in algae, resulting in decreased photosynthetic activity.[59] The effects of ammonia toxicity on algae were investigated by Abeliovich and Azov.[60] It was found that ammonia at concentrations over 2.0 mg/L and at pH values over 8.0 inhibited Scenedesmus obliquus, a dominant species in high-rate oxidation lagoons.

Zooplankton mortality has been found to be correlated with high pH values. The pH values observed to kill zooplankton, however, were higher than would normally be observed in lagoons.

Odours occur under anaerobic conditions. Lagoons are most susceptible to odour problems during ice breakup before aerobic conditions prevail. Fisher et al. found, after examining data from Alberta and Saskatchewan, that odours were probably related to high sulphate concentrations in the municipal water supplies.[61] In all cases of severe odours, the sulphate content was greater than 400 mg/L.

Anaerobic reduction of sulphates and sulphur-containing organics results in the production of H_2S, mercaptans and other sulphides. Inhibition of algal activity will occur if the average sulphide concentration is greater than 4.0 mg/L.[62] Un-ionized H_2S is pH dependent and toxic to aquatic life at very low concentrations. The Ontario Ministry of the Environment has set an objective of less than 0.2 mg/L un-ionized H_2S for all receiving waters.

Sulphide production in laboratory-scale ponds was studied by Gloyna and Espino, who produced a regression equation relating organic loading and retention time to the production of sulphide.[62]

4.2.2 Chemical Influences. Dissolved oxygen concentration is a significant factor determining the rate and level of aerobic treatment. Aerobic processes are preferable since they are faster and less temperature sensitive than anaerobic processes. Diurnal algal oxygen levels during the warm months may fluctuate from supersaturated conditions during daylight to severely depressed levels at dawn. Dissolved oxygen concentrations are reduced with the onset of winter, giving rise to anaerobic conditions until ice break up. Low oxygen levels from either organic overloading or reduced algal activity may contribute to odour problems during summer months.

Alkalinity in a lagoon system is capable of buffering the aqueous system and is a source of carbon for autotrophic organisms such as algae. If alkalinity is too low, there may be insufficient carbon dioxide available for algal metabolism, causing photosynthesis to be inhibited.

High pH induced by photosynthetic action may cause reductions in alkalinity by calcium carbonate ($CaCO_3$) precipitation. This could be of potential significance in some areas of the north where water of low alkalinity occurs. This type of problem is related to the bedrock geology. Igneous and metamorphic regions have little buffering capacity in their surface waters to prevent wide variations in pH, whereas sedimentary basins have adequate alkalinity to ensure good buffering. The high diurnal variations in pH observed in southern lagoons have not been observed in the north, even though the buffering capacity of the water is lower. This phenomenon has not been explained.

4.2.3 Natural Disinfection. The lagoon environment is hostile to many enteric organisms, both pathogens and nonpathogens. Mechanisms contributing to natural disinfection include:

1) sedimentation,
2) sunlight,
3) biotoxins,
4) phages,
5) algae,
6) pH,
7) organic loading,
8) adsorption, and
9) nutrient deficiencies.

Mitchell and Chamberlin found that sedimentation and sunlight were significant factors in the removal of indicator organisms, with algal toxicity related to sunlight.[63] They discounted any contribution from biotoxins or phages.

Parhad and Rao found that Escherichia coli died faster in the presence of algae and at a pH greater than 10.[64] Other studies indicated that because of the sensitivity of E. coli, high pH was more likely the cause of death.[65, 66] McGarry and Bouthillier found that the rate of Salmonella die-off was related to the organic loading.[67] Virus removal has been attributed to adsorption to solids and subsequent sedimentation.

Bacterial removal kinetics are assumed to be first-order, and various authors have applied chemical reactor engineering to model lagoon efficiency.[68, 69] A consistent problem has been the evaluation of the rate constant "K". The parameters which most affected "K" were temperature, organic loading, and algal concentration.

4.3 Influences of Lagoon Conformation/Operation

Generally, the designer controls the physical elements of lagoon construction and therefore can provide the desired interconnecting and flow control structures to suit the design.

4.3.1 Lagoon Type. Three types of lagoon systems are presently in use:

a) anaerobic,
b) anaerobic and facultative with storage, and
c) facultative with storage (seasonal).

Anaerobic lagoons have short retention times (3 to 5 days), are fairly deep (3 to 6 m) to ensure anaerobic conditions throughout the basin, have a relatively small surface area to minimize surface aeration, and are heavily loaded (kg BOD_5/m^3). The second system involves a number of anaerobic cells followed by facultative cells with optional storage ponds for total retention as required. Facultative lagoons are designed on a loading basis, e.g., 22 kg BOD_5/ha-d, or 247 people/hectare which is approximately equivalent to a retention time of 100 days. Storage ponds provide additional retention capacity where required. These ponds are usually built to the same specifications as the facultative cells to a total water depth of 1.5 to 2.4 m.

4.3.2 Number and Shape of Cells. Multi-celled lagoon systems operated in series have been used to reduce short circuiting and to obtain improved effluent quality. Short circuiting describes the condition where the residence time is less than theoretical. Short circuiting is a serious problem in lagoons, with poor geometry being the major cause. Multi-celled lagoons also provide for a progression of organisms from lower to higher animals for improved water quality.

Dawson and Grainge suggested using multiple-cell lagoons to provide extra storage during maintenance operations such as sludge removal.[70]

Marais reported improved microorganism removal in lagoons in a series configuration.[69] Zickfoose and Hayes recommended series operation during the summer to reduce the algal content of the effluent.[71] They also recommended the use of parallel lagoons to reduce the organic loading on a lagoon system operated under winter conditions.

Rectangular ponds have been recommended for ease of construction and efficient land utilization, with length:width ratios from 1:1 to 2:1 providing good plug flow conditions. Others have recommended 3:1 maximum ratio with shapes of any type to suit the topography.[72] Mangelson and Watters recommended large L:W ratios to promote plug flow conditions.[73]

Inlet-outlet devices should be located so to minimize short circuiting. It has been suggested and supported that short circuiting can be overcome by using outlet structures that allow the operator to control the influent and effluent elevations in the water column.[9] Most regulatory agencies recommend centrally located discharge points.[24]

4.3.3 Discharge Control for Optimum Performance. Discharge may be either continuous or intermittent, or the flow may be totally retained.

Continuous discharge is the normal operating mode in temperate climates since seasonal variations of effluent quality are small. Historically, many lagoons located in cold regions were also designed for continuous discharge.

Controlled intermittent discharge is now the preferred method to compensate for the lack of treatment in winter months and for short circuiting. Discharge is often regulated for spring and/or fall release to take advantage of the dilution water in the spring and the higher quality effluent in the fall.

Series operation is the usual mode when organic loading permits, since higher effluent quality is obtained. Parallel operation to lower the organic loading on the first cell during the winter and other periods of low dissolved oxygen is desirable when odours are a problem. For larger, multi-celled systems, optimum efficiency may be obtained using a combination of parallel and series operation.

Total retention relies upon seepage and evaporation to maintain a liquid balance in the lagoon. The total retention concept of balancing the inflow with evaporation and seepage losses resulting in no surface discharge is not common in Canada, mainly for climatic reasons.

The problem of when to discharge was recently addressed by Hatcher who suggested the use of hydrographs to determine discharge periods compatible with maximum dilution.[74]

The designer must provide adequate piping, valving and level control devices to permit a choice of series, parallel or combined use of cells so the operator may discharge the best effluent quality possible.

5 FACILITY PLANNING

Once the decision has been made to consider a sewage lagoon to meet the waste treatment and disposal requirements of a particular client, the physical facility must be planned with respect to siting, conformation, construction, operation and maintenance. Details on siting and constructing municipal engineering projects, including waste treatment facilities, are documented in the "Cold Climate Utilities Delivery Design Manual".[37, 39]

The U.S. Environmental Protection Agency's "Design Manual: Municipal Wastewater Stabilization Ponds", summarizes the current methods used for designing lagoons including mathematical modelling methods.[75] Middlebrooks et al. provide an excellent summary of design approaches and resulting performances.[11]

5.1 Site Selection

The following aspects of site selection are addressed here:

a) geotechnical considerations in the presence of permafrost,
b) public health concerns, and
c) effluent disposal considerations.

5.1.1 Geotechnical Considerations in the Presence of Permafrost. To ensure a stable earth structure, a general knowledge of soil types and ground thermal regimes at potential sites is necessary. Some information related to permafrost and frozen soils in general was provided in Section 3.

Construction materials required at the site include soil suitable for berm construction, or impervious material (clay) for lining the lagoon when coarse - grained soils predominate. Surface drainage should not be altered at the site since thermal degradation may be accelerated by the combination of ponded water and warmer ground temperatures which occur beneath waterbodies.[76]

Preliminary information can be obtained from aerial photographs and special information maps available from various government agencies. This preliminary investigation should determine available information related to geology and topography, vegetation, groundwater condition, climate, logistics, and environmental impacts.

A detailed on-site study of the ground thermal regime and the engineering properties of the frozen and unfrozen soils by a competent geotechnical specialist should follow.

Soil sampling and testing are carried out using the same standard procedures used in warmer regions.[77] Care must be taken to obtain high quality samples so that representative strength and permeability values for the soil types can be determined.[78]

Test pits should be used to provide information on soil ice conditions, ease of excavation, and groundwater conditions. In addition, *in situ* infiltration tests can be conducted if the soil is not frozen.

Temperature measuring devices such as frost tubes and thermistors installed at the site will give information on thaw depth and soil temperature as a function of depth and time throughout the seasons. This will allow the identification and location of frozen and unfrozen soils.

5.1.2 **Public Health Concerns.** Public health aspects of lagoons centre on:

a) human safety around the lagoon, requiring fences and warning signs; and
b) potential contamination of surface and groundwaters by pathogens in discharged treated effluents.

Feachem et al.[9] compiled a state-of-the-art review of sanitation, disease, and the effectiveness of various sewage treatment processes. They found that a properly designed lagoon was the best process for reducing pathogens.

In warm climates, properly designed and operated lagoons, operated in series, are capable of producing secondary quality effluent with faecal coliform levels less than 200 per 100 mL. Once water temperatures drop below 15°C to 20°C indicator organisms that persist longer and less than two $\log_{10}$ unit reductions are common. The impact of releasing large numbers of indicator organisms into the environment is largely unknown; however, recent research suggests that public health could be threatened by organisms with transferable drug resistance.[79]

The persistance of microorganisms has been reported in the literature to be mainly a function of temperature and time. McGarry and Bouthillier reported temperature and organic loading to be important in the survival of *Salmonella typhi* in a lagoon.[67]

Most lagoons discharge effluents to surface waters. In cold climates, these waters are frozen over for six to eight months of the year and water temperatures are near freezing. Smith and Gerard[80] speculated that lagoons allow microorganisms to escape thermal shock by providing gradual acclimatization. Slanetz et al.[81] carried out a study of bacterial and viral survival in a lagoon system in New Hampshire and noted that higher persistance was found during the winter months.

Gordon[82] and Davenport et al.[83] reported indicator persistance 2.7 to 5.4 times longer in arctic rivers than previously reported for southern winter conditions. Dahling and Safferman[84] found enteric viruses had a survival rate of 34 percent over a 320 km reach of the Tanana River in Alaska. This supported earlier findings by Prier and Riley[85] who found that Echovirus, Coxakievirus, and Poliovirus were stable in 4°C river and impoundment waters. Viable viruses can be stored indefinitely at deep-freeze temperatures and long survival times can be expected at 0°C to 5°C.[86] Clarke et al.[87] described results suggesting that viruses may remain viable for greater than 200 days at temperatures lower than 4°C. They also found that Poliovirus survived three times longer than E. coli and Streptococcus fecalis. Bitton[88] reported virus survival of 40 to 90 days at 3°C to 5°C under laboratory conditions. Yamamoto[89] reported the initial findings on the virus content of lagoon effluents in the Northwest Territories and locations in Alberta. He found substantial numbers of viruses at all locations. This supported earlier reports of viruses in lagoon effluents on a regular basis.[81, 90] Berg and others have reported similar findings in all climates[87, 91, 92]. This poses a serious health hazard since the infective dose of viruses is small.

There is evidence that microbes remain viable for long periods in cold climate lagoons and that large numbers of pathogenic bacteria and viruses are being discharged into the environment.

The incidence of R^+ organisms is playing an increasing role in outbreaks of drug resistant bacterial epidemics. The problem of transferable R factors was first discovered by Japanese researchers in 1959 while studying the outbreak of drug resistant Shigellae. The phenomenon results from a group of plasmids - extrachromosomal genetic structures composed of DNA - called resistance transfer factors (R factors) which are able to travel by cell to cell contact.[15]

R factors are responsible for acquired resistance to antibiotics, toxins, heavy metals, ultraviolet light, bacteriocins, and phages. The ability of Enterobacteriaceae to transfer R factors amongst themselves has serious implications for public health. Grabow et al.[79] reviewed the problem in depth and noted that Enterobacteriaceae act as reservoirs for R factors and will transfer them to pathogens. They suggested that water quality standards should be reviewed in light of R factors.

Bell et al.[93-95] investigated the occurrence of R factors in the sewage flora of northern Canada and the Prairie Provinces. The remote northern Slave River had low incidences of antibiotic-resistant faecal coliforms, 7.1 percent having multiple drug resistance and 0.79 percent having transmissible drug resistance. This differed markedly from the Red River in Manitoba where Winnipeg waste discharges are a major source of drug-resistant faecal coliforms, 52.9 percent having multiple drug resistance and 18.77 percent having transferable resistance. They found 10.8 percent of the faecal coliforms in raw sewage had R factors, as did 8.9 percent of the total coliforms. The authors speculated that 9 to 11 percent of the natural flora in the Red River have R factors and that these organisms appear to compete favourably in the aquatic environment.

Sewage lagoons appear to be ideal environments for R+ organisms. Kish and Lampky[96] studied a long retention time, seasonal discharge lagoon in Michigan and found that total coliforms persisted over the winter months with numbers peaking at 10^7 per 100 mL during the spring turnover. Proportions of drug-resistant organisms decreased over the winter but increased through the three-pond system. Summer samples were not taken. More than 60 percent of the total coliforms in the effluent showed drug resistance. Bell et al.[95] reported the survival incidence of R+ faecal coliforms in a continuous discharge, long retention lagoon system at Fort Smith, Northwest Territories. They found that the proportion of R+ organisms increased over the winter. The effluent faecal coliform population contained 58 percent with resistance to three or more drugs and 4 percent with transferable drug resistance.

5.1.3 Effluent Disposal Considerations. Effluent disposal alternatives include:

a) surface waters;
b) wetlands;
c) land;
d) groundwater recharge (seepage pits); and
e) total retention (evaporation).

Effluent disposal alternatives must be assessed to avoid the potential for the exposure of people, animals, or the environment to adverse effects. The persistence of pollutants in surface waters, on land, and in groundwater may create serious problems if not accounted for in the planning process.

Where feasible, full advantage should be taken of the capacity for dilution by extending outfalls to areas where natural mixing is optimal. The designer must determine the highest water level of the receiving stream so that the level of the lagoon may be determined to permit the desired discharge.

Lagoons should not be located on floodplains or in intertidal areas. Peak flows in northern rivers occur during the spring thaw, creating problems for treatment facilities located on a floodplain. Lakeside facilities must be located to avoid ice and high water damage to structures. Oceanside lagoon design must account for high tides and waves caused by storms.

Seasonal high flows in surface waters may cause ice scour at lagoon outfalls. Erosion of river banks and unstable soil conditions may also combine to cause structural failures in the outfall sewer. In permafrost areas particularly, care must be taken to recognize the potential impact of thermal degradation when open outfall channels are used. Care should be taken not to alter existing drainage basin patterns.[97]

The discharge of lagoon effluents into wetlands has shown some promise in the north, but few detailed studies have been carried out. The proximity of a swamp or wetland to a lagoon should prompt consideration of this method. The extent of the wetlands use (trapping, hunting, etc.), and potential human health impact must be considered prior to using this method of disposal.

Some information is available on land disposal of treated effluents.[61] Many areas with continuous permafrost are unsuitable, particularly where fine-grained soils are present. This aspect should be reviewed during the field geotechnical investigation. Sletten suggested that thawed areas adjacent to major water bodies may be suitable for land application since permafrost is deep or absent.[98] The impact on the quality of the adjacent water body should be assessed during the planning stage.

Scientific data are lacking to adequately assess evaporation as an alternative in the north. The total-retention lagoon may require a very large surface area; therefore, land acquisition may be a problem and capital costs may be unjustifiable. If evaporation is considered, detailed analysis of several years of evaporation data is necessary to adequately design the facility.

The depth to groundwater and soil conditions will determine if groundwater recharge of lagoon effluent is a viable alternative where surface water disposal is not possible. There is a paucity of published literature, however, on groundwater discharge using seepage pits or wells in cold climates. Warnings of groundwater contamination by microbes and nitrates should groundwater recharge be used are found in the literature.[39]

Groundwater occurs in three forms in permafrost regions: sub-, intra-, and supra-permafrost. The first two types are not normally of interest since surface water has no access except under special circumstances. Supra-permafrost groundwater may enter lagoon berms during the summer.

Although frozen ground exerts a retarding influence on groundwater flow, it should not be considered impermeable. Soils may contain air, water, ice, or a mixture of ice and water; permafrost should be considered as a confining bed of low but finite permeability.

The organic surface material has an important role in determining the drainage pattern at a given site. In the thawed state, due to the high hydraulic conductivity of the organic surface layer, available surface water infiltrates the upper layer. Factors that govern whether the water will continue downward into the mineral soil include:

a) hydraulic properties of the mineral layer, and
b) the rate of infiltration into the organic layer.

During the summer, the organic surface material is similar to a shallow acquifer confined by the underlying mineral soil which may be relatively impervious. This is particularly true if the active layer is thin where the organic surface layer acts as a conduit, moving the groundwater rapidly downslope.

5.2 Physical Configuration

The number, size, depth, shape and elevation of the cells depend on the process design and the local site conditions. Tilsworth and Smith provided the design summary shown in Table 5.

5.2.1 Process Design. The two main criteria used in designing lagoons are retention time and organic loading. Retention time is a critical factor in stabilizing organic matter and removing pathogenic organisms. Most jurisdictions use a minimum residence time as a fundamental design requirement. The design requirements of provincial regulatory agencies are summarized in Table 6, prepared by the Municipal Services Division, Technical Services and Contracts Branch, Indian and Northern Affairs Canada.

Organic loading is the oldest criterion for sewage lagoon design and, over the years, experience has produced the surface loading rates that are commonly used in temperate climates.[53]

The U.S. EPA design manual tabulates designs based on conventional approaches and it was found that an organic loading of 11 to 22 kg BOD_5/ha-day was as reliable as any of the rational models when sizing a lagoon for regions where ice cover forms.[72] This approach, however, has failed to meet effluent standards under continuous flow conditions in cold region lagoons.

Canter et al. reported typical BOD loading rates across the United States, demonstrating a trend towards reduced loading and longer retention times at higher

TABLE 5 DESIGN SUMMARY[70]

General Design	Long Retention Lagoons	Short Retention Lagoons
1) Maintain simplicity of construction and operation.	1) For populations < 500	1) For populations < 2000
2) Avoid permafrost where possible.	2) Detention time 8 to 12 months.	2) Use in series with secondary long retention lagoons or other acceptable treatment.
3) Berm Construction: a. use non-frost susceptible soil b. use impervious materials c. maintain 0.3 to 0.9 m freeboard d. provide minimum top width of 2.4 to 3 m e. provide embankment slopes; horiz./vert. = 2:1 to 6:1	3) BOD_5 loading = 1.8 to 3.6 kg/ha·day	3) Detention time 5 to 30 days
4) Cell Construction a. Shape - circular, rectangular or square b. Impervious floor material - liners where necessary c. Series arrangement, 2 to 3 cells	4) Provide sludge storage.	4) Depth 3 to 7.5 m
5) Liquid Levels a. minimum depth after drainage (15.2 cm) b. liquid depth beneath ice (1.4 m) c. provide additonal 0.9 to 1.8 m for ice formation	5) Consider; a. springtime supplemental aeration b. rock filters c. land applications and treatment	5) BOD_5 loading = 32 to 82 kg/ha·day
6) Drainage-direct, away from lagoon.	6) Disinfection prior to discharge to a receiving water.	
7) Install fencing and warning signs.	7) Evaluate existing swamps, ponds, lakes and marshes for potential use.	
8) Location; a. locate minimum of 0.4 to 0.8 km from a community b. locate minimum of 0.4 km from residences c. locate downwind of prevailing wind direction		

TABLE 6 TYPICAL PROVINCIAL DESIGN AND EFFLUENT QUALITY CRITERIA FOR CANADIAN SEWAGE LAGOONS (Indian and Northern Affairs Canada)

Province	Loading	Effluent Quality (mg/L)	Detention Time	Other
Nova Scotia	20 lb BOD_5/acre•day (22.4 kg/ha•d) 100 gal/cap•day (454 L/cap•d) 0.17 lb BOD_5/cap•day (0.19 kg//ha•d)	BOD 10 stream SS 10 BOD 30 ocean SS 30	60 days	chlorination
Prince Edward Island	35 lb BOD_5/acre•day (39.2 kg/ha•d) 200 people/acre (81 people/ha) 60 gal/cap•day (272.4 L/cap•d)	BOD 20 SS 20 provided 10:1 dilution available	120 days	nil
New Brunswick	34 lb BOD_5/acre•day (38.1 kg/ha•d) 200 people/acre (81 people/ha) 0.17 lb BOD_5/cap•day (0.19 kg/ha•d)	BOD 20 SS 20 provided 8:1 dilution available	60 days	case specific
Ontario	24 lb BOD_5/acre•day (26.9 kg/ha•d)	BOD 15 SS 20	approx. 365 days	phosphorus removal to 1 mg/L
Manitoba	50 lb BOD_5/acre•day (56.1 kg/ha•d) 200 people/acre (81 people/ha)	BOD 30 SS no limit	186 day operating capacity	nil
Saskatchewan	30 lb BOD_5/acre•day (33.6 kg/ha•d) (primary cell)	N/A	2 cells secondary cell 180 days	cells in series
Alberta	50 gal/cap•day (227 L/cap•d)	BOD 15-30 SS 15-100	365 days ND 3 years evaporation pond	nil

latitudes.[99] They recommended 22 kg BOD_5/ha•day as a maximum for regions with seasonal ice cover. Dawson and Grainge supported this value as a criterion for northern Canada.[73]

Design by surface loading rate establishes the mean hydraulic residence time. McKinney noted that the surface loading rate is established by the retention time if depth is kept constant.[8]

5.2.2 Site Considerations. Identification of the feasibility of cut and fill operations is necessary at an early stage in the design. Factors that affect this decision are the location of the water table, type of soil, thermal conditions, and the proximity of the borrow material. High water tables in coarse-grained or silty soils may require costly dewatering, and present uplift problems with a lined structure.

Generally in permafrost areas, as the amount of permafrost increases, the design approach will be to maintain the existing permafrost surface as the lagoon base. The design depth of the proposed lagoon will be achieved by constructing berms to the required height. The possibility of dredging material for construction purposes should not be overlooked.

A monograph edited by Johnston entitled Permafrost: Engineering, Design, and Construction is an excellent compendium of northern geotechnical engineering.[36] It provides data of interest to cold climate lagoon designers, including engineering characteristics of frozen soils, ground thermal analysis, cold regions project planning, cold regions earthwork, and the design of dams and reservoirs in cold regions.

The standard reference, Design of Small Dams, provides detailed design approaches to earth and rock structures.[41] Basic design criteria include:

a) the necessity for maintaining stable side slopes under all conditions of construction and operation, particularly during periods of drawdown;

b) consideration of stresses imposed on the foundation by the lagoon embankments particularly if the thermal conditions are altered in ice-rich soils;

c) analysis of seepage flows through the embankment to eliminate possible excessive neutral stresses from occurring and to predict possible hydraulic piping conditions which may cause structural failure; and

d) lagoon embankment protection against overtopping and wave action.

5.2.3 Berm Stability. The physical size and height of the berm required to contain the wastewater depends on:

a) the required volume determined during design including treatment requirements, plus sludge and ice;
b) the available surface area and depth of the lagoon; and
c) the side slopes.

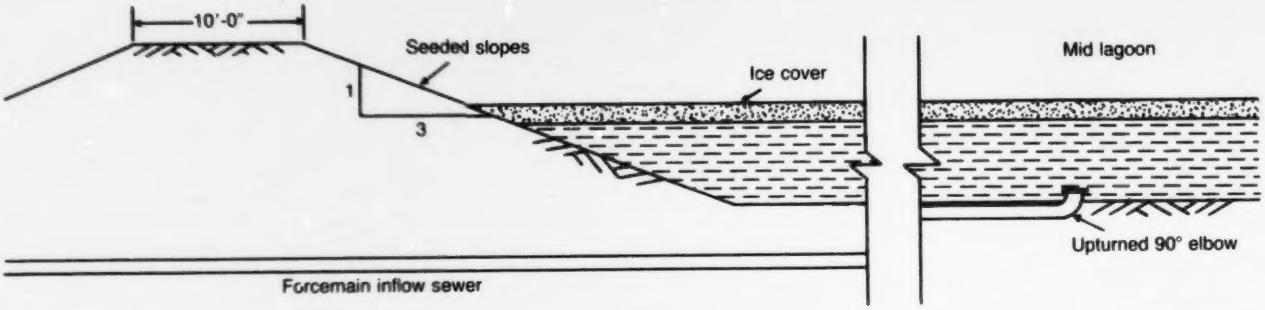
Dawson suggested that berms be as steep as possible to provide maximum volume in a minimum area.[7] An opposite view was taken by Fielding who found that berm erosion by wave action was severe at steep slopes and recommended 4:1 (horizontal:vertical) as maximum for clay soils.[100] Flatter slopes will increase the shallow area of the lagoon, resulting in more nuisance vegetation.[14] Side slopes between 3:1 and 6:1 on the inner slope were reported to limit potential damage from ice and waves. The exposed slopes of the berms should be capped with riprap or seeded to reduce erosion. A typical cross-section of a lagoon facility is provided in Figure 8.

Water from the active layer (suprapermafrost) may enter lagoon berms during the summer through capillary action, increasing the moisture content in the berm material. This will lead to changes in the thermal properties of the berms and instability may develop in the long-term. During freezing periods, this may contribute to frost heaves in the berms.

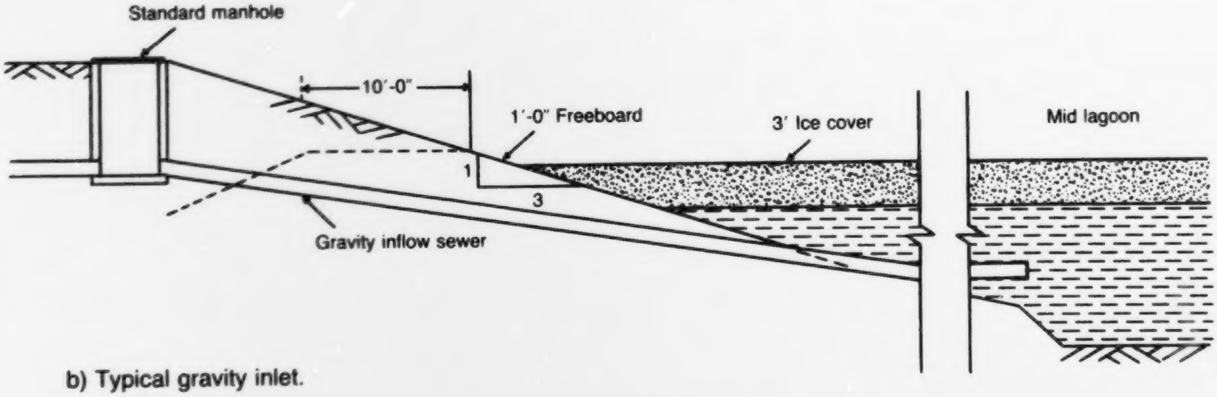
Lagoon embankment design in permafrost regions follows the same criteria as given for earth structures, but consideration of the impact of the lagoon on the ground temperature regime beneath the lagoon must be analysed. Typical thaw bulbs which form under water impounding earth structures are shown in Figure 9.

It is impractical to prevent lagoons from disturbing the ground thermal regime; therefore, embankment design must account for thaw settlement. Knowledge of soil properties, soil and ice interfaces, and identification of ice-rich areas is necessary to predict thaw settlement. Earth structures can accommodate a certain amount of uniform settlement. The usual method of evaluating settlement is to apply a one dimensional thaw consolidation model modified from Terzaghi's Theory of Consolidation.[101] Embankments have been successfully built on frozen ground using frozen material. Foundation settlements of 1.8 metres were anticipated for the dykes at the Kelsey River generating station in northern Manitoba. The design accommodated the settlement and no special measures were taken to prevent thawing of the ice-rich foundation soils.

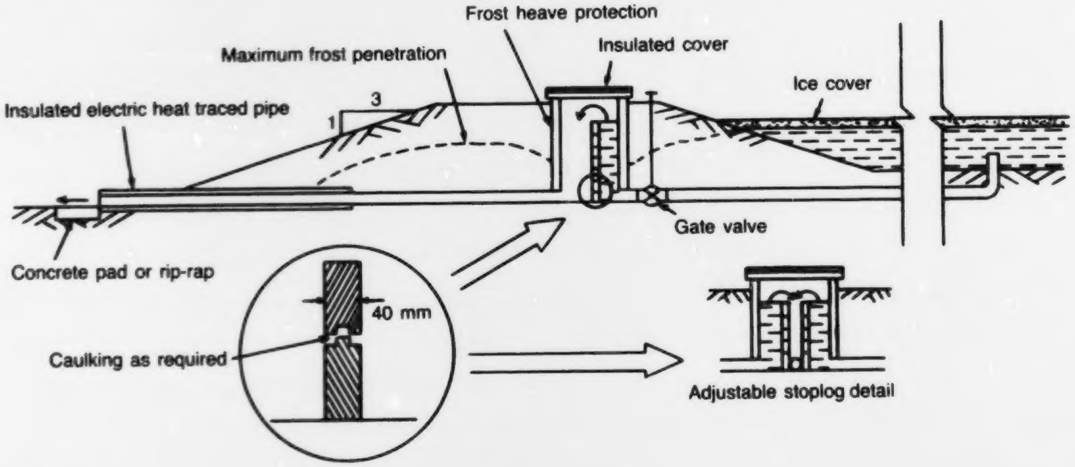
Seepage into the berm from the lagoon can be prevented by using clay that is not susceptible to frost. Peat can be placed to form the core of the berms since it is fairly impervious when frozen and will have a lower thermal conductivity than other soils.


10'-0"
Seeded slopes
1
3
Ice cover
Mid lagoon
Upturned 90° elbow
Forcemain inflow sewer

a) Typical forcemain inlet.


Standard manhole
10'-0"
1'-0" Freeboard
3' Ice cover
Mid lagoon
1
3
Gravity inflow sewer

b) Typical gravity inlet.


Frost heave protection
Insulated cover
Maximum frost penetration
Ice cover
Insulated electric heat traced pipe
3
1
Gate valve
Concrete pad or rip-rap
40 mm
Caulking as required
Adjustable stoplog detail

c) Typical outlet arrangement.

FIGURE 8 TYPICAL BERM CROSS-SECTIONS[39]

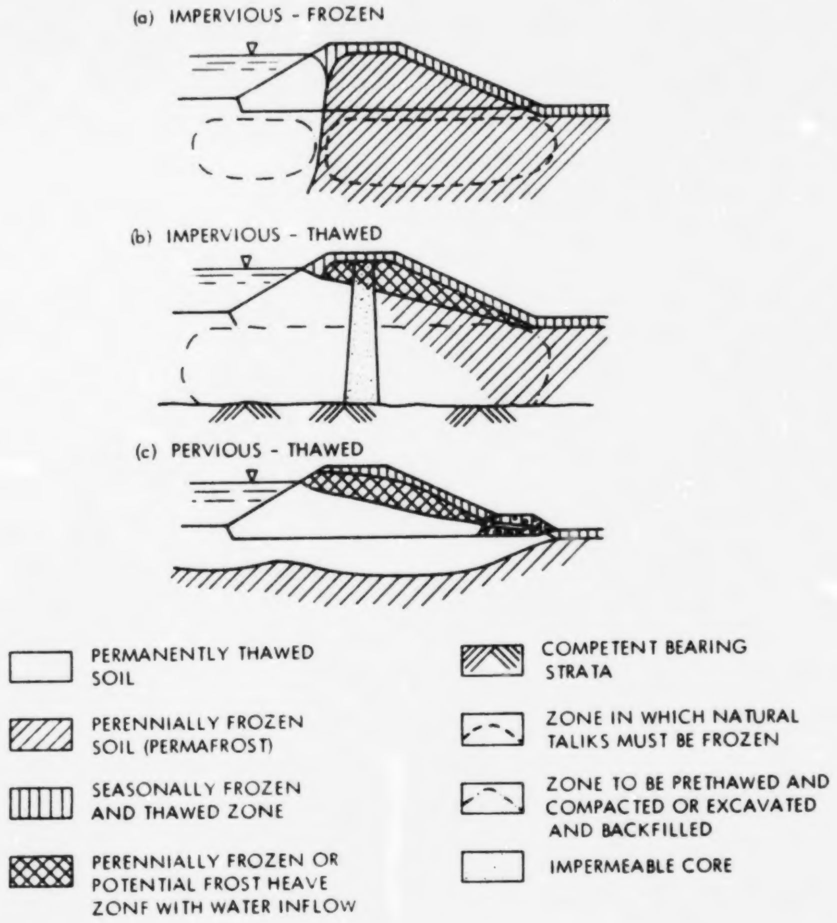

(a) IMPERVIOUS - FROZEN
(b) IMPERVIOUS - THAWED
(c) PERVIOUS - THAWED
PERMANENTLY THAWED SOIL
PERENNIALLY FROZEN SOIL (PERMAFROST)
SEASONALLY FROZEN AND THAWED ZONE
PERENNIALLY FROZEN OR POTENTIAL FROST HEAVE ZONF WITH WATER INFLOW
COMPETENT BEARING STRATA
ZONE IN WHICH NATURAL TALIKS MUST BE FROZEN
ZONE TO BE PRETHAWED AND COMPACTED OR EXCAVATED AND BACKFILLED
IMPERMEABLE CORE

FIGURE 9 THERMAL REGIMES OF BERMS ON PERMAFROST[37]

Factors to be considered when selecting a liner include:

a) membrane compatibility with the contained substance;
b) required service life;
c) seepage criteria;
d) possible membrane abrasion;
e) whether a supported or unsupported membrane is required; and
f) the climate, including wind direction and speed, and temperature.[102]

Examples of liner materials include concrete, asphalt, soil cement, spray-on sealants, compacted clay, clay admixtures, ice and synthetics.[103] Asphalts and soil cements are subject to shrinkage cracks, tension cracks and inconsistent application. The high permeability which may result renders these liner systems unacceptable for wastewater lagoons. Acres Consulting Services Ltd. evaluated various sealant techniques and the stability of spray-on products when exposed to cold climatic conditions and found them unsuitable.[104] Their ability to withstand differential movement was low.

A thick layer of well compacted clay will provide a lining for the lagoon. Care must be taken not to let the liner dry as it may crack.[105] Irregularities within the compacted clay liner such as silt and sand seams, and fissures can affect the permeability. One clay which has been used is bentonite which is known for its swelling characteristics when mixed with water. At least 30% clay is required to effect a seal and reduce permeability.[106] The swelling property of bentonite and its sealing ability are jeopardized, however, when in contact with a liquid containing high cationic concentrations. This may limit its use as a liner for lagoons.

A synthetic liner is believed to be the best alternative for a wastewater lagoon in the north. Synthetic liners are available with different chemical compositions, physical characteristics, waste compatibilities, and methods of installation. Consideration should be given to the following properties when selecting a synthetic liner:

a) mechanical properties;
b) overall weathering;
c) temperature characteristics;
d) overall field splicing;
e) coefficient of permeability; and
f) cost.

Failure of a liner is often due to poor design, or installation and operation, but seldom to the lining material itself.

5.2.4 **Appurtenances.** Appurtenances may include inlet pipes, truck unloading facilities, flow control devices, outlet structures and outfalls. These must be incorporated into the design of the earth structure and be included in the thermal analysis. Various ancillary devices are illustrated in Figure 8.

Thaw settlement can have a severe impact on the structural integrity of appurtenances. Seepage along the pipe/soil interface must be minimized by the use of cut-off walls. Where local conditions permit, the inlet conduit may be placed over the berm rather than through it.

Outfall structures require special attention. For the design of a surface outfall, four critical time periods must be recognized:

a) fall freeze-up;
b) extremely low temperature periods in the winter;
c) spring breakup; and
d) high flow periods.

The type of water body and the nature of the ice formed are also important.

In the fall, frazil ice formed by the supercooling of the receiving water may block a submerged outfall. During periods of very low temperatures, both freefall and subsurface outfalls may be blocked with ice. This must be accounted for in design.

Northern communities with trucked waste collection systems require special unloading facilities that are convenient to the user. A trucked waste disposal facility should provide access in all weather, to all kinds of vehicles, with minimum grades on the approaches. Other desirable features are discussed in the literature.[39]

5.3 Construction Considerations

Earthwork is one of the most critical activities concerning the engineer working in a cold climate. The task of scheduling a construction project in the north is an important one. Information obtained during the site investigation concerning soil types, groundwater, and equipment suitability will assist in the scheduling activity. The possibility of staging the construction over the summer and winter should be evaluated.

In both permafrost and non-permafrost regions, summer construction and the use of unfrozen soil will enable construction of a well-compacted berm and liner. Cold weather compaction and the use of frozen material results in poor densities and unstable berms. These methods may be forced upon the designer by access problems and/or a short construction season.

5.3.1 Subgrade Preparation. A lagoon site in an area with organic surface materials requires one of the following:

a) removing all peat, which may be a very costly unless the deposit is thin;
b) consolidating the peat beneath the berm fill resulting in settlement for a long period after construction has finished; or

c) floating fill on the peat surface where the fill is thin.

The decision to remove peat from a site in a cold climate region should not be made hastily. Many people are of the impression that peats are "weaker" than soft clays because of their greater compressibility. Peats gain strength with compression, however, and their ability to withstand shear forces is enhanced.[107]

Removal of overburden in continuous permafrost zones may rapidly degrade the soil thermal regime, reducing the site to a quagmire. If possible, surface deposits should remain undisturbed in warm ice-rich permafrost soils.

5.3.2 Excavation. Kays recommended that the berm subgrade be compacted to 95% of Standard Proctor density to provide a uniform crust on which to carry out fill placement.[108] Where permafrost exists, fill should be placed early in the spring before the active layer has had time to develop, to retard the development of a thermokarst situation beneath the berms and within the lagoon.

As the temperature decreases, excavation of all saturated soils becomes more difficult. Homogeneous frozen soils are generally more difficult to excavate than stratified soils. The lower moisture content of sands present within silt and clay layers provides weak planes for ripping. Since sand and gravels often have lower moisture contents than silts and clays, they are usually easier to excavate. Detailed studies have been carried out by the U.S. Army Cold Regions Research and Engineering Laboratories (CRREL) into the excavation of coarse as well as fine-grained soils. Moore and Sayles provide a summary of this work and a detailed bibliography.[109]

Organic soils are difficult to excavate due to their high moisture content and degree of saturation. Although the organic mat provides support for equipment when frozen, the excavation of frozen peat is very difficult. Ripping the peat before using scrapers may increase the rate of progress.

Controlled blasting may be used to excavate frozen soils. Proper design of charges and their placement will allow accurate excavations to be made. Small charges will break the frozen material into easily excavated pieces. Final grading of the lagoon excavation must provide for drainage to a low point and present smooth contours.

5.3.3 Embankment Construction. A berm is an engineered fill requiring compaction quality control. Many factors affect soil compaction, including grain size, moisture content, temperature, and compactive effort.

The methods used to build berms in northern regions during the summer are similar to methods used in the south. The fill material will need exposure to warm air to promote melting of ice prior to placing in the fill section.

Coarse-grained soils can be replaced frozen, provided that the moisture content is low, since there will be little thaw settlement. If the soil matrix is saturated difficulties in compaction may occur, even though the material could be excavated.

Frozen clay is difficult to use for winter construction and large settlements and instability may result when the clay thaws. One method of avoiding this problem is to stockpile frozen material during the summer where it can thaw and drain. Silty soils should be avoided since they have a very narrow density range at their optimum moisture content.

It is difficult to compact frozen material. The resulting low density is believed to cause excessive settlement and loss of stability after the soil thaws. If high quality compaction of berms is required, the material must be placed in an unfrozen state during the summer.

Conventional compaction equipment may be used, although the compactive effort required may be higher to obtain suitable densities at the over optimum moisture contents likely to occur.

5.3.4 **Synthetic Liner Installation.** The minimum temperature at which the liner may be installed is given by the manufacturer. This limits installation of many types of synthetic liners to the summer months. Supervision of the work should be provided by the supplier of the liner.

A protective layer placed on the subgrade will protect the liner from puncturing and tearing by material in the subgrade. Melting of the soil will be retarded if the protective layer between the heat source and the frozen ground has insulative characteristics. An underlay of polyurethane blankets (foamed onto sacking) beneath the liner may provide the required thermal insulation and form a protective bedding for the membrane. Sawdust may also be used as a bedding material or for protection from overburden.[110]

The rolls of lining should be oriented around the site so that when unrolled they will be properly positioned. Orientation markings should be printed on the liner as well as the wrapper. To reduce brittleness the folded liner may be heated using forced air heaters before being placed. The liner should be placed when the wind is low and ballasted with sandbags until anchored in place. The seams should be perpendicular to the toe of the slope so that any strain will not pull them apart. Liners should be anchored on top of the berms so that they do not blow away or pull off the side slopes. The membrane should be placed in a trench dug on top of the berm and, backfilled and compacted to hold it in place. Care must be taken during installation that workmen do not damage the liner. Equipment should not be allowed to ride on it except under conditions recommended by the manufacturer. The liner should be installed with a five percent overlap to accommodate differential settlement of the subgrade.

A compacted soil cover should be placed over the liner. This protects the liner from the effects of exposure to infrared and ultraviolet light. The cover may act as a ballast if water collects beneath the liner and will also provide protection from ice and surface waves. Kays[108] suggests a minimum lift thickness of 150 mm, whereas Matrecon Inc.[111] recommends 460 mm. Wave action may cause cyclic increases in pore pressure in the soil cover resulting in sloughing of the side slopes. Low side slopes and good compaction will help to maintain a soil layer on the berms. Flat side slopes allow the ice sheet to ride up the slope without damaging the liner.

Allen et al. concluded in their research that in a dry, distilled or saline water environment freeze/thaw cycling has no appreciable influence on the load-strain-strength characteristics of geotextiles.[112] A decreased rate of creep for polypropylene geotextiles was associated with a reduction in temperature. Their experiments also showed that subfreezing temperatures do not adversely affect the load-strain-strength and creep characteristics of the material. Failure by differential settlement need not occur if good site investigation practice and design are utilized. Flexible and thicker membranes can tolerate more differential settlement without damage.

Local depressions and soft spots may exist on the subgrade. The placement of geotextile over the subgrade may act to bridge these areas and thereby improve the performance of the total berm.

5.4 Operation and Maintenance

A well-designed and constructed lagoon may fail to meet pollution abatement objectives if not operated and maintained properly. In fact, marginal lagoons can produce good quality effluent if operated in a diligent fashion.

The need for training may not seem important but to have a system which fulfills the designer's goals and the taxpayer's expectations, there must be a moderately skilled operator to maintain and operate a lagoon system.

Karn provided a list of the basic equipment requirements for a lagoon operator including lawn mowers, valve keys, and appropriate hand tools.[113] Depending on the size of the facility, the equipment requirements can be quite modest.

The best available training material is the Water Pollution Control Federation (WPCF) and Environment Canada publication WPCF Wastewater Treatment Skill Training Package: Wastewater Stabilization Ponds.[114] Another document of value is Zickfoose and Hayes', Operations Manual: Stabilization Ponds, U.S. EPA.[72]

5.4.1 **Operation.** The operation of a lagoon involves performance monitoring and flow control.

Lagoon performance should be monitored by the operator, particularly prior to effluent discharge. Records should be kept of raw wastewater characteristics, flow rates and effluent characteristics. Samples should be routinely collected and sent to a laboratory for analysis. Sludge accumulation should also be measured along with weather conditions, lagoon and wastewater temperature, and snow and ice cover.

The operator should be given specific instructions on using the flow control devices provided at the lagoon so he may operate them to achieve the best effluent quality possible. Selecting the correct time, rate and quantity of discharge to protect the receiving waters and leaving enough volume behind so the lagoon may continue to perform at maximum efficiency are also important.

Middlebrooks et al. stressed the need for choosing the correct time and rate of discharge to protect receiving waters.[11] They outlined the usual procedure for intermittent discharges as did the authors of the EPA design manual.[75] Only enough wastewater to provide the next storage volume should be discharged since the effluent will benefit from maximum retention times.[115]

5.4.2 **Maintenance.** Routine inspection and maintenance of berms and appurtenances are requirements for trouble-free operation. Valves, control manholes, and outfall structures are often neglected until the time comes for use, resulting in costly delays.

Short growing seasons in the north hamper the establishment of ground cover on the embankments. Provision for interim slope stabilization should be made at the time of construction. The operator must watch out for berm erosion and take appropriate action if necessary. Animals such as gophers and muskrats can cause serious leakage problems which eventually may lead to embankment failure. These animals should be discouraged from living adjacent to or in the lagoon.

Aquatic weeds and other vegetation which limit light penetration, prevent mixing and harbour nuisance insects may be discouraged by maintaining water depths greater than 1.0 metre.[116]

In ponds with excessive vegetation, the mosquito is the most frequently found nuisance insect. Fair et al. reported that Culex tarsalis (the vector of equine encephalitis) favoured lagoons due to the presence of algal carbon dioxide (CO_2).[16] Reports on mosquito breeding originate in regions where the problem is not as intense as in the North. No studies on mosquito breeding in northern lagoons were found in the literature reviewed.

Schneiter found little information on sludge removal in cold climate lagoons.[47] The usual practice is to drain the cell and use earth moving equipment.[117] Suction dredges have also been used to clean lagoons. Where parallel operation is possible, a single cell may be by-passed for dewatering and cleaning.

Most odour problems occur in the spring and are of short duration, unless a lagoon system is severely overloaded. Treatment for odour problems has included parallel operation of ponds, treatment with sodium nitrate ($NaNO_3$), supplementary aeration and recirculation of oxygen rich effluent.[72]

6 UPGRADING LAGOON EFFLUENTS

Various alternatives have been proposed and used to upgrade lagoon effluents:

1) chemical treatment;
2) auxiliary aeration;
3) filtration methods,
    - intermittent sand filters,
    - rapid sand filters,
    - rock filters, or
    - microscreening;
4) land application,
    - slow rate infiltration,
    - overland flow,
    - rapid infiltration, or
    - wetlands disposal; and
5) aquaculture and biological enhancement.[11]

Several U.S.A. publications deal with upgrading options for lagoons.[118-124] Many of the reported techniques concern BOD and suspended biological solids removal. Algae, which may contribute to unacceptable BOD and nutrient loads in the receiving environment comprise the bulk of these solids.

Nutrients contribute to eutrophication of natural waters. Existing low eutrophication levels can amplify the impact of concentrated waste nutrients in northern rivers and lakes. Phosphorus and nitrogen removal may be necessary as an upgrading step for some lagoon effluents.

Only chemical treatment, auxiliary aeration, and land treatment have been investigated as upgrading methods in northern lagoon applications.[70, 125, 126, 127]

Disinfection of cold climate lagoon effluents has been promoted because cold temperatures can extend the survival times of pathogenic bacteria and viruses.

6.1 Chemical Treatment

6.1.1 Disinfection. The presence of persistent microorganisms in ice-covered lagoons and rivers warrants concern. Ozone and ultraviolet radiation are among the most effective disinfectants in cold temperatures. Though more costly than chlorine, both have less environmental impact and neither are toxic to fish.

Various arguments for and against disinfection have been presented.[128] Controversy has surrounded the use of chlorine in terms of the public health benefits of reduced microbial populations, toxicity to aquatic forms of life and, the impact of carcinogenic halogenated organics.

The need for power and/or the cost of chemicals has generally discouraged the disinfection of lagoons in cold climates. International Environmental Consultants Ltd. (1978) presented a matrix that associated the impact of disinfection alternatives on biological, socio-economic, and physical-chemical aspects. Disinfection with lime and chlorine exerted the most pronounced effects.[55] Chlorination-dechlorination treatment indicated a lesser impact.

Some of the problems of cold climate disinfection of wastewater were addressed by Chambers[129], whose criticism was that most research for cold water applications had been done on synthetic test waters.

Chlorine. The efficiency of chlorinating lagoon effluents has been reviewed.[130] Chambers presented data comparing the effect of hypochlorus acid on E. coli and three types of viruses noting that the virucidal effect of chloramines was very low.[129]

Chlorine deactivates some viruses at a faster rate than chloramine formation.[131] The viruses are not necessarily affected by chlorine in the same way that coliforms are affected.[132] Coliphages are more resistant to chlorine disinfection than coliforms.[132]

Treating lagoon effluents with chlorine causes the destruction of algal cells, resulting in a higher BOD in the effluent. Attempts have been made to reduce adverse effects by using chlorine dosages not toxic to algae but effective against coliforms. These efforts have been met with limited success as controlling the dose was difficult. The presence of chlorine-resistant microorganisms not represented adequately by coliforms makes this an unattractive method.

Johnson[133] noted that the reduction in the rate of chlorine disinfection for lagoon effluents at cold temperatures was partially offset by reductions in the exertion of chlorine demand. The net effect, however, was a reduction in the chlorine residual necessary to achieve adequate disinfection.

The Ontario Ministry of the Environment conducted laboratory tests on the chlorination of six lagoon effluents used for spray irrigation. Although much variability was observed, it was concluded that a 4 mg/L dose and 10 minute contact time could reduce the total and faecal coliform densities to acceptable levels. It was implied, however, that because of the initial highly variable bacteria densities, overdosing might have been necessary. A high algal concentration in the lagoon effluent was instrumental in preventing high bacterial reductions. Temperature was not considered as a variable. Insufficient data were collected to define mathematical relationships between the measured chlorine residual and the various effluent quality parameters evaluated. The viability of actually dosing lagoon contents was not discussed.

Another problem with chlorine disinfection is the potential toxic effect on receiving water biota. Chlorine persists longer at low temperatures and a synergistic effect may occur with oxygen starved biota at the naturally low dissolved oxygen levels in northern waters.[129, 134] Dechlorination with sulphur dioxide gas or other reducing agents may be necessary.

On the basis of existing data International Environmental Consultants Ltd.[55] concluded that chlorination-dechlorination was the most cost-effective, environmentally acceptable disinfectant for lagoon effluents.

Ozone. Ozone has been shown to be an effective disinfectant at low temperatures. The time required for disinfection is short and toxic residuals are minimal (dissolved oxygen is a decomposition product). A serious disadvantage is that the ozone must be generated on-site since it is unstable and reduces to oxygen.

Given and Smith[135, 136], found three to four log reductions of indicator organisms at 20 to 40 mg/L ozone when raw, dilute wastewater was treated. Lagoon contents with a similar BOD required a similar ozone dose. They observed increased indicator organism reductions with decreasing temperatures. Additional benefits were reductions in COD, BOD, and increased dissolved oxygen concentrations. Some cost aspects were explored by IEC[55], which concluded that ozone was not presently cost effective.

Lime. Lime is an effective disinfectant at high pH and practical contact times. Some advantages of using lime are that it is relatively insensitive to low temperatures and to organic concentrations, and that a 30 minute contact time at pH 11.5 to pH 12 will provide effective disinfection.

The use of excess lime disinfection at low temperatures has been investigated by Morrison and Martin[137] and Schneiter[47]. Morrison and Martin found temperature was less important than pH, where disinfecting ability was concerned. An average lime dosage of 430 to 1000 mg/L was required for raw sewage, while 250 to 435 mg/L may be adequate for secondary effluents.[138]

Some problems with the use of lime are:

a) the pH must be greater than 11.0 for effective disinfection, and may have to be adjusted afterwards; and
b) sludge accumulation increases in the lagoon (it may be recycled, however).

IEC[55] concluded that lime disinfection would annually cost about an order of magnitude more than chlorination.

Ultraviolet disinfection. Ultraviolet disinfection of wastewater has been suggested as the most promising process currently available. Advantages may include:

1) no change in wastewater characteristics because no chemicals are added to the effluent;
2) no danger of overdose;
3) relatively simple operation; and
4) high bacterial inactivation within seconds.

6.1.2 Coagulation and Flocculation. In situ chemical coagulation of controlled discharge lagoons can be very effective in removing BOD, COD, SS, nutrients, and microorganisms. Where phosphorus removal is necessary the addition of chemicals to enhance coagulation and flocculation is the most cost-effective method. The choice of chemical for a particular installation depends on factors such as the delivered cost, the quantity of chemical required, the ease of handling, storing and application, percent removal desired, and the amount and type of sludge produced.[139]

Several researchers have studied the effectiveness of alum under various temperatures and in different modes. Some findings of interest were[126, 140, 141]:

1) high phosphorus removal was achieved;
2) best results were obtained during periods of ice cover;
3) BOD removal increased by 2.5 with alum addition; and
4) the addition of alum to raw sewage followed by a precipitation basin before the lagoon proved most effective.

Graham and Hunsinger[142] found that alum was most cost-effective in comparison with lime and ferric chloride ($FeCl_3$) and that it did not seem to retard biological activity. It was also found to be easy to handle in liquid form.

Pollutech Pollution Advisory Services Ltd.[143] found 200 mg/L alum to be optimal in reducing phosphorus in lagoons to below 1 mg/L. Higher temperatures increased phosphorus in the effluent. This agreed with the work of Al-Layla and Middlebrooks which indicated that when alum was used, algal cell coagulation decreased as temperatures rose.[28] Resolubilization of phosphorus was found to be minimal and could be controlled by adding alum. Low dissolved oxygen concentrations also influenced resolubilization. Severe wind conditions hampered good suspended solids free effluent. Most researchers using $FeCl_3$ found good removals but the chemical was difficult to handle and the cost was high.

Disadvantages in using lime include cost and dosage required, both being higher than the cost and dosage for $FeCl_3$ or alum. More manpower is required; more sludge is produced; substantial releases of phosphates, BOD, and SS after treatment are caused; and additional equipment for preparation and dispersion are required. Also, it was found that heavier doses of lime were necessary during extremely cold temperatures to effect the same removal.

6.2 Auxiliary Aeration

In some cases, it is desirable to upgrade the lagoon effluent by auxiliary aeration which may allow increased loading without concomitant odour problems.

Several reports focus on instances of overloaded facultative lagoons being converted successfully to mechanically aerated facultative lagoons.[144, 145] Information on the performance of aerated facultative lagoons in Alaska was found in several sources.[146-152]

Aeration also discourages stratification thereby minimizing short circuiting. BOD loading on aerated lagoons was reported to be five to ten times that of a facultative lagoon.[153] Champlin[154] stated that 127 kg $BOD_5/1000\ m^3$ was the upper limit for supplementary aeration, while Boulier and Atchison[153] indicated 48 kg $BOD_5/1000\ m^3$ was a typical upper limit. Temperature is a major factor in determining these limits.

There is a small, inexpensive floating aerator adaptable to northern climates with a submersible motor resistent to freeze up.[155] Most northern applications have used diffused aeration since mechanical aerators have proven unreliable under heavy ice conditions.

From the literature it was suggested that an oxygen supply of 0.45 to 0.68 kg O_2/kg BOD_5 should be supplied to satisfy BOD loading.

A minimum aeration power input of 0.75 kW/1000 m^3 of lagoon volume to ensure availability of dissolved oxygen in all parts of the lagoon was recommended.[156] Reid[147] presented an example to determine the brake horsepower for an air pump.

Under anaerobic conditions during the spring thaw, floating aerators could provide needed aeration on a temporary basis.[68] Provision must be made for benthic oxygen demand from accumulated sludge in the spring. Marais indicated oxygen demands at this time may exceed three to five times the influent BOD load.[157]

The Ontario Ministry of the Environment has undertaken pilot and full-scale studies on aerating lagoon effluents to remove hydrogen sulphide H_2S.[158] Although some difficulty was experienced in maintaining sufficient liquid depth to ensure efficient oxygen transfer, the results were felt to be satisfactory.

In another laboratory experiment, a post aeration column was utilized. Although impressive effluent hydrogen sulphide removals were achieved, the odour problems originating in the preceding lagoons were not overcome. Effluent aeration for hydrogen sulphide removal was more cost effective than aerating the whole lagoon contents. Added benefits of this method were said to be increased dissolved oxygen and the oxidation of other materials in the effluent.

6.3 Filtration

Filtration technologies may be applied to lagoon systems to reduce the suspended solids and BOD in effluents. Three types of suspended solids removal systems were investigated during the summer months in southern Ontario by Rupke and Chisholm.[159] These included chemical addition followed by filtration, and microscreening. A 23-μm stainless steel cloth was used on the microstrainer. Mixed media filtration with anthracite and sand in a 0.2 m^2 filter having a nominal feed rate of 14.7 m/h was found to be the most effective method.

Wittman et al.[160] conducted extensive field testing using a 1-μm polyester fabric for algae removal and found microscreening to be a viable process free of earlier problems associated with using the corrodable 23-μm stainless steel cloth. Microscreening effectiveness may be independent of pH or the volume of algae present. The life expectancy of a plastic 20-μm screen was reported to be two years or more.[160, 161]

Metcalf and Eddy suggested that effective treatment could be attained when microscreening is coupled with sand filtration.[2]

6.4 Land Application

Land application is limited by soil conditions (permeability, permafrost) and the thermal regime of the area. A recent U.S. EPA report provides a comprehensive discussion on all aspects of land treatment of municipal wastewaters.[162] Middlebrooks et al. reviewed applications to lagoon effluent upgrading and stated that regions with severe winters may require effluent storage facilities.[11]

Contamination of the groundwater is a major concern in the application of wastewater to the land surface. High ammonia and nitrate levels may occur in groundwater posing a potential health hazard for infants where used for water supply. Most microorganisms remain in the upper metre of the soil horizon due to adsorption and filtration.

6.4.1 Infiltration. Rapid infiltration has the greatest potential for northern applications. The large volume infiltration basins conserve heat, vegetation is not required to obtain treatment, and the role of bacteria is reduced. Disadvantages may include soil freezing during cold periods, reliance on suitable soil conditions for permeability and thawed stability, and potential groundwater pollution.

Alaskan rapid infiltration basins operating during the summer months establish a soil heat regime which reduces frost penetration in the winter.[96] This is enhanced by snow and ice accumulation. The U.S. EPA manual[162] lists some infiltration system modifications for use in cold regions:

a) mowing grassy or weedy areas and disking prior to freeze-up, to prevent grass and soil freezing the ice cover to the ground;
b) digging a ridge and furrow system in the basin surface which helps create an ice bridge and prevents the "lid" from sticking to the ground; and
c) using snow fences to promote drifting over the basin which improves heat retention in the water and soil.

Slow-rate land applications have been studied intensively.[163-166] Purification relies on soil microorganisms and a cover crop of plants to remove organic matter and nutrients. These processes are inhibited or halted by snow and cold temperatures. The presence of fine-grained, occasionally ice-rich soils with low permeability, cold ground temperatures, and a short growing season have limited the use of this method in the north.

A follow-up study on land application of sewage two years after irrigation was performed by SNC Tottrup Services Ltd.[167] The study areas included Fort Simpson, Norman Wells and Tuktoyaktuk, NWT. The researchers concluded that sewage had a negligible effect on the native vegetation two years after application. Land application of sewage was not recommended, however, as a major disposal method in permafrost areas, because of rapid saturation of the soil and the potential for contamination of groundwater and surface water.

6.4.2 Wetlands. Nichols[168] reviewed the dynamics of nutrient removal in wetlands. He stated that removals of phosphorus and nitrogen can be very high, at low cost. Hartland-Rowe and Wright[169], Slupsky and Firth[170], and Shaw[171] studied the Hay River, NWT wetland disposal system. Hartland-Rowe and Wright recommended that *Carex* (sedges) be used as a wetland plant, and that at least a 10-km flow path be available to achieve adequate reductions of microorganisms and BOD.[169]

Black et al.[172] studied the feasibility of using artificial wetlands to upgrade effluent from an Ontario lagoon. They reported results suggesting that artificial marshes could be used in treating lagoon effluents and concluded that retention time, configuration, flow rate, and temperature were the most important parameters. Poor winter performance was reported.

Effluent quality data is site-specific but the literature suggests that BOD removals from secondary effluent of 70 to 90 percent are attainable in wetlands as well as nitrogen removals of 40 to 60 percent.

Peatland disposal is another alternative. Labonte et al.[173] and Dubuc et al.[174] have reported encouraging results with the disposal of raw wastewater on peatlands in northern Quebec. Metcalf and Eddy reported that high removals of phosphorus, nitrogen, and fecal coliforms were obtained in a Minnesota peatland investigation.[2]

6.5 Aquaculture

Biological enhancement through aquaculture in cold regions has been reported by Serfling and Alsten[175], Pershe[176], and Reed and Bouzoun[177]. Daborn et al.[178] studied the ecology of *Daphnia* in a Nova Scotia sewage pond in the winter and summer. Neil investigated the feasibility of removing phosphorus, nitrogen, and organic matter through biological uptake and harvest of algae, duckweed, *Daphnia* and midge larva in Ontario sewage lagoons.[179]

Other options in aquaculture include fish, a variety of zooplankton, and water plants such as water hyacinths and cattails.

Romanenko[180] reported on a batch addition of selected algae to improve spring BOD removal following spring break-up. Beyond noting a four-fold decrease in BOD, no other information was presented.

SUMMARY

The report provides an overview of the important factors which should be considered when siting, designing, constructing, operating, and maintaining lagoon systems in cold climates.

Lagoons are often the most economical alternative for wastewater treatment in cold climates. Approximately half of the 1750 treatment systems inventoried in Canada in 1981 were sewage lagoons with 70 percent in the northwest. Their summer performance is comparable to that of southern lagoons but during winter is inconsistant deteriorating to that of a sedimentation basin. The treatment performance data available are difficult to interpret because of incomplete or poorly detailed sampling procedures which prohibit a meaningful comparison of influent and effluent data.

Lagoons are biologically complex, dynamic systems precluding to-date the development of usable and reliable mathematical models. In particular, the role of psychrophilic organisms in lagoon treatment is poorly understood. Enhancing the performance of microorganisms within lagoons by biological modification may increase their efficiency in cold climates.

There are many physical factors affecting lagoon performance in cold climates: temperature, thermal stratification, sunlight, wind, and ice and snow cover. Cold temperatures decrease the digestion rate resulting in increased sludge accumulation. Improved on-site consolidation by biological or chemical means is required to optimize lagoon sludge management. Thermal stratification and thermocline formation are beneficial as better distribution of the raw sewage from the inlet is promoted. Liquid depth and surface area are the important factors involved in thermocline formation. Pond configuration should promote wind access to maintain well mixed conditions within the lagoon. Ice and snow cover reduce the amount of incoming light which has an adverse effect on photosynthetic reoxygenation and contributes significantly to the anaerobic conditions found in northern lagoons.

Natural disinfection by predation and UV light results in effluent with good biological quality during the summer. Predictions of efficiencies and optimization of these processes may allow the development of higher quality effluents, or an extension of the time during which acceptable quality effluent is produced. Chemical disinfection of lagoon effluents is required during periods when, and at locations where, public health concerns exist. The inefficiencies of chlorine disinfection, difficulty in controlling the chlorine dosage, and undesirable end products have frequently resulted in a decision

against its use. Alternative methods of disinfection are available at increased cost and therefore are slow to be adopted.

The major public health concern associated with lagoons in cold climates is the fate of indicator and pathogenic organisms. Are they indeed being acclimatized in lagoons? What is the relationship between indicator and pathogen concentrations in cold water? Does the treatment system promote transferable drug resistance? What happens to viruses, endospore-forming and cyst-forming organisms? All of these questions need to be answered by means of well-designed studies.

Riverbank outfalls result in a discharge plume which follows the shore downstream where public contact is most likely to occur. Outfall location and the need for effluent distribution to minimize the mixing zone should be given serious consideration in light of this potential health hazard.

The use of swamplands or wetlands as disposal or upgrading options has been tried and appears to be successful. Further research on this approach should yield valuable design information.

The disposal of lagoon effluents onto thaw-unstable soils may cause significant changes to the biological and thermal characteristics of the receiving environment. Erosion of protective vegetation and soil layers contributes to increased thawing, in turn leading to increased surface ponding. Methods of predicting and preventing this situation are required.

The design of cold climate lagoons has undergone significant modification in effort to produce acceptable quality discharges to the environment. Decisions to reduce loading rates, increase retention time, and eventually use a seasonal discharge mode of operation are based on visual observations and limited analytical information.

In cold climates, retention time has become the main design parameter. This usually involves long holding periods with one or two discharges per year; however, many existing units operate on a continuous flow basis. Evidence suggests that continuous flow systems operate best in a plug flow hydraulic regime. The performance of existing continuous flow systems, could be enhanced by the development of an ice-resistant baffling system to reduce short circuiting.

Multiple cells have been used to approach plug flow conditions. The number of cells in series have ranged from two to seven or more. The number of cells, configuration, retention times, and the type of inlet-outlet structures to be used may be specified by the regulatory agency or may be selected by the designer.

The presence of permafrost may result in unstable soil conditions which can adversely affect the lagoon structure. Geological understanding of frozen soils has increased greatly over the last two decades and general guidelines for the use of frozen soils as foundation materials have been developed. In the presence of permafrost expensive measures must be taken to preserve the thermal integrity of the soil. In this case, it may be more economical to use an alternative form of wastewater treatment or to use another site.

Lagoon embankment design and performance, types of foundation soils and their state, and the types of embankment material available require more detailed investigation.

The nature of drainage control features for local runoff and seepage need to be examined. The problems associated with creation of a warm thermal window in an otherwise frozen soil can present major problems with impermeable membranes. Designs related to the use of controlled uplift pressure relief valves in the base of the lagoon through the liner and the decisions as to where they should discharge cannot be made with current knowledge.

The operation of a lagoon involves performance monitoring and flow control. The operator should be given specific instructions on using the flow control devices provided so that they may be operated to achieve the best quality effluent to protect receiving waters, and to seed the next storage volume. Regular maintenance of berms and appurtenances must be provided. On occasion it may also be necessary to combat odours, aquatic weeds, or mosquitoes.

Lagoon cleaning and the disposal of the resulting sludge is a maintenance problem which recurs on a five to ten year cycle. This may prove to be a difficult problem for lagoons with a synthetic membrane liner.

Lagoon effluent upgrading can be implemented by improving performance or adding tertiary treatment. Effluent polishing can be achieved by positive effluent control (seasonal discharge), effluent filtration and chemical treatment. The conversion of existing lagoons to partially mixed units to relieve overloaded or odiferous conditions merits further study.

This overview confirms the continuing need to further examine and expand our knowledge and understanding of cold climate sewage lagoon systems. The challenge is to ensure by more rational and precise design and operating methods that the sewage lagoon systems remain cost effective while meeting increasingly more stringent environmental and public health requirements.

GLOSSARY

AEROBIC	requiring air or free oxygen to maintain life processes
ANAEROBIC	air or free oxygen not required to maintain life processes
AUTOTROPHS	organisms capable of manufacturing organic nutrients from raw inorganic materials
BENTHIC ZONE	the area relating to the bottom or bottom environment of a body of water
BOD (biological/ biochemical oxygen demand)	the amount of dissolved oxygen required to meet the metabolic needs of aerobic microorganisms in water rich in organic matter, such as sewage
COD (chemical oxygen demand)	a quantitative measure of the amount of oxygen required for the chemical oxidation of carbonaceous (organic) material in wastewater using inorganic dichromate or permanganate salts as oxidants in a 2-hour test
CYANOTROPHS	blue-green algae
EPILIMNION	a freshwater zone of relatively warm water in which mixing occurs as a result of wind action and convection currents
EUCARYOTIC	cells that contain a distinct membrane-bounded nucleus, characteristic of all organisms except bacteria and blue-green algae
FACULTATIVE LAGOON	a lagoon or treatment pond with an aerobic upper section and an anaerobic bottom section so that both aerobic and anaerobic biological processes occur simultaneously
FAECAL COLIFORM (FC)	bacteria associated with faecal matter of warm-blooded animals - identification in water indicates presence of faecal contamination
FUNGI	organisms which have a nucleus, are sporebearing and do not contain chlorophyll
GRAM-NEGATIVE BACTERIA	are bacteria that stain red when using the differential bacteriological stain "Gram's Stain" - distinguished from gram-positive bacteria, which stain blue
HETEROTROPHS	organisms incapable of manufacturing organic compounds from inorganic raw materials, therefore requiring organic nutrients from the environment

HYPOLIMNION - the lower level of water in a stratified lake, characterized by a uniform temperature that is generally cooler than that of other strata in the lake

PERMAFROST - perennially frozen ground, occurring wherever the temperature remains below 0°C for several years, whether the ground is actually consolidated by ice or not and regardless of the nature of the rock and soil particles of which the earth is composed

PHAGES (bacteriophages) - a virus that attacks bacteria

PHOTOSYNTHESIS - synthesis of chemical compounds in light, especially the manufacture of organic compounds from carbon dioxide and a hydrogen source, with simultaneous liberation of oxygen, by chlorophyll-containing plant cells

PROCARYOTIC - cells that lack a membrane-bounded nucleus; found only in bacteria and blue-green algae

PROTOZOA - a diverse phylum of eucaryotic microorganisms

PSYCHROPHILIC - thriving at a low temperatures

SHORT CIRCUITING - a hydraulic condition occurring in parts of a lagoon where the time of travel is less than the flowing-through time

SUBPERMAFROST - the layer of ground below the permafrost

SUPRAPERMAFROST - the layer of ground above the permafrost

THERMOCLINE - a temperature gradient in a body of water, in which the temperature decrease with depth is greater than that of the overlying and underlying water

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